Presented at The Ohio State University, Aerospace Engineering and Aviation Spring 29002 Seminar Series, April 25, 2002

Glenn-HT: The NASA Glenn Research Center General Multi-Block Navier-Stokes Heat Transfer Code

Raymond E. Gaugler, Chief, Turbine Branch

For the last several years, Glenn-HT, a three-dimensional (3D) Computational Fluid Dynamics (CFD) computer code for the analysis of gas turbine flow and convective heat transfer has been evolving at the NASA Glenn Research Center. The code is unique in the ability to give a highly detailed representation of the flow field very close to solid surfaces in order to get accurate representation of fluid heat transfer and viscous shear stresses. The code has been validated and used extensively for both internal cooling passage flow and for hot gas path flows, including detailed film cooling calculations and complex tip clearance gap flow and heat transfer. In its current form, this code has a multiblock grid capability and has been validated for a number of turbine configurations. The code has been developed and used primarily as a research tool, but it can be useful for detailed design analysis. In this presentation, the code is described and examples of its validation and use for complex flow calculations are presented, emphasizing the applicability to turbomachinery.

Glenn-HT: The NASA Glenn Research Center General Multi-Block Navier-Stokes Heat Transfer Code

By

Raymond E. Gaugler
Chief, Turbine Branch
NASA Glenn Research Center

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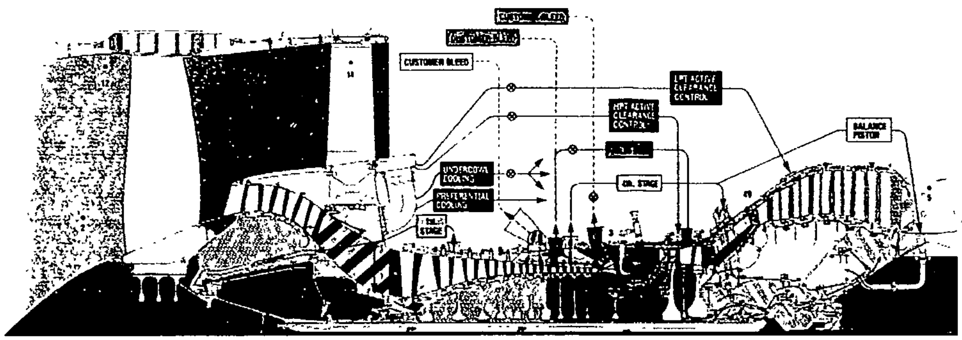
OUTLINE

- **NASA Glenn Turbine Branch**
- **Glenn-HT History**
- **Glenn-HT Capabilities**
- **Glenn-HT Sample Validation Cases**
- **Glenn-HT Future Direction**

GE 90 ENGINE AIRFLOW



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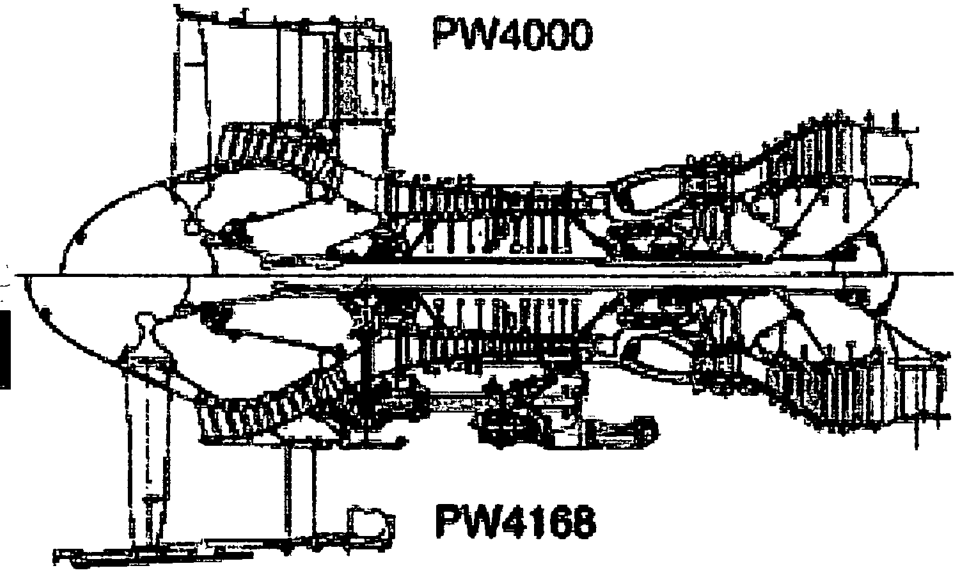

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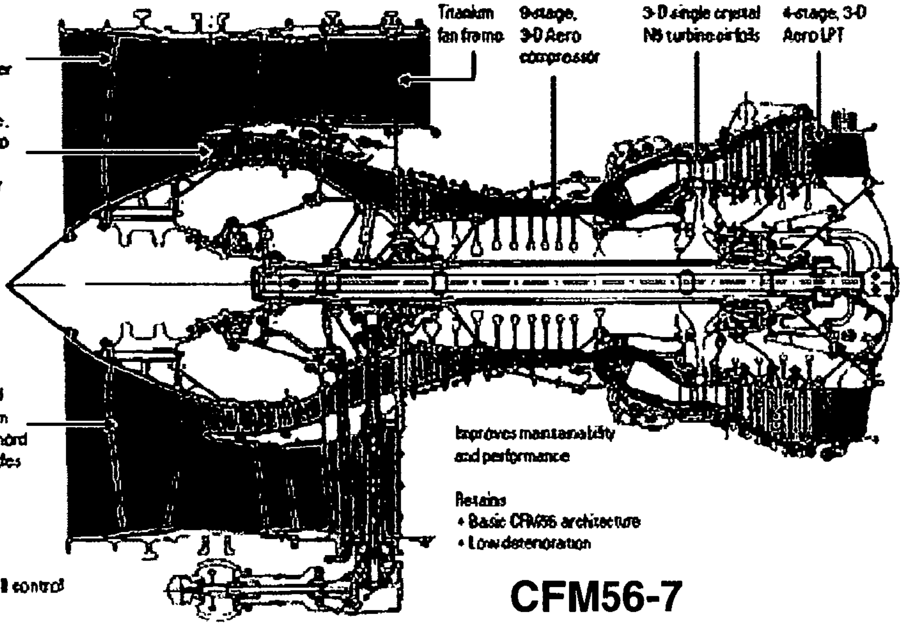
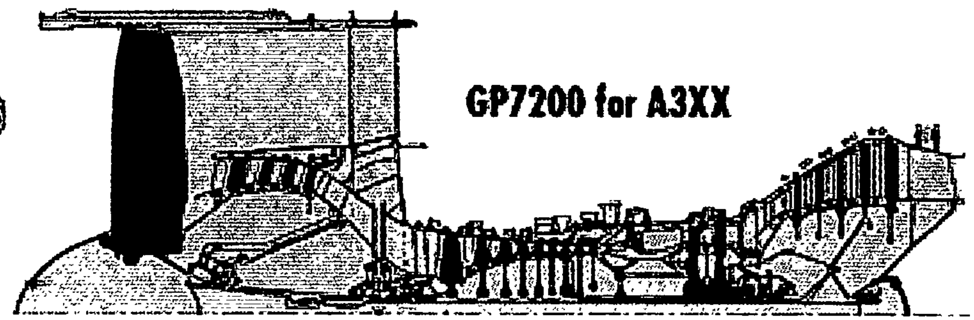


CFM56-7



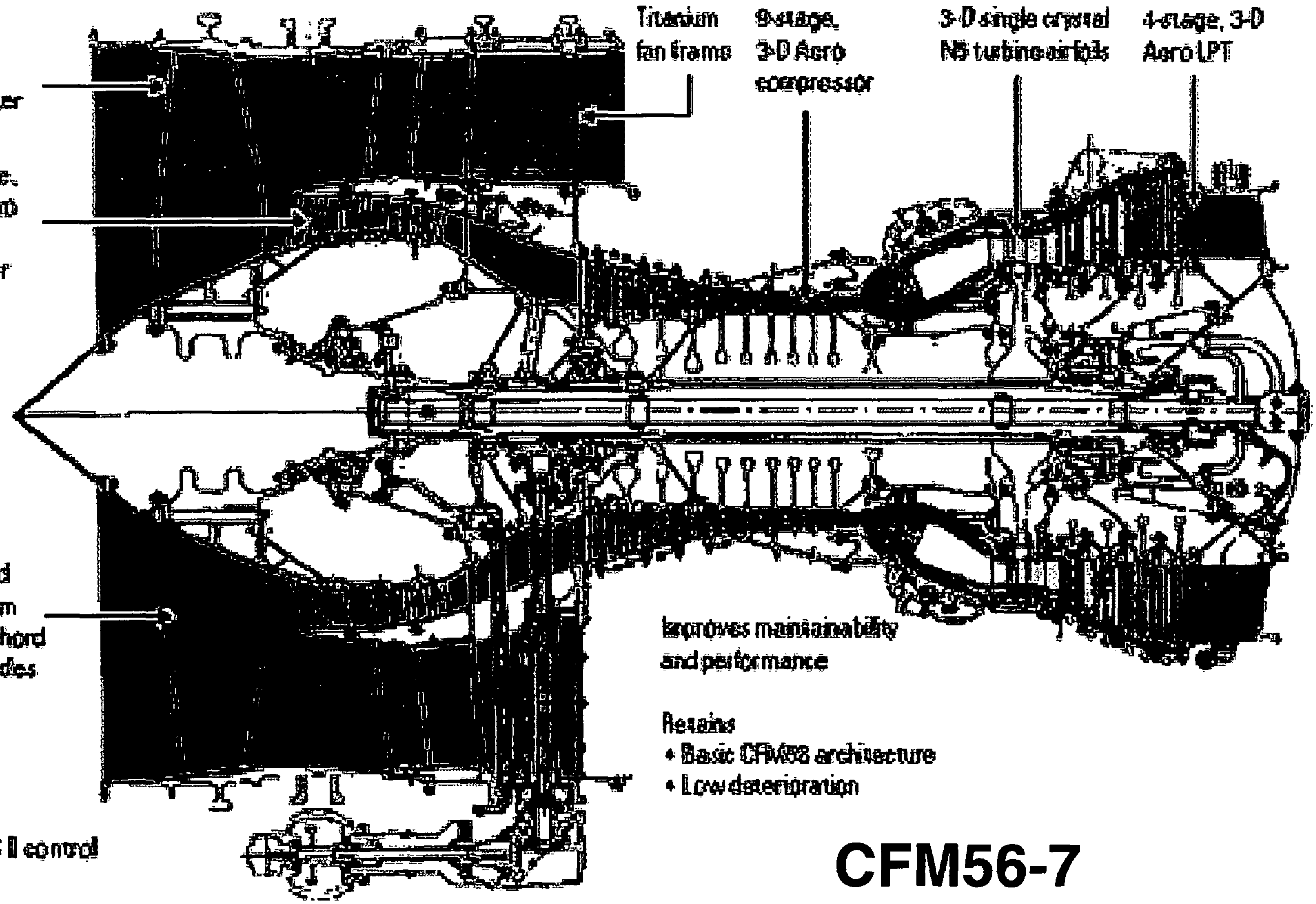
GP7200 for A3XX

Glenn Research Center

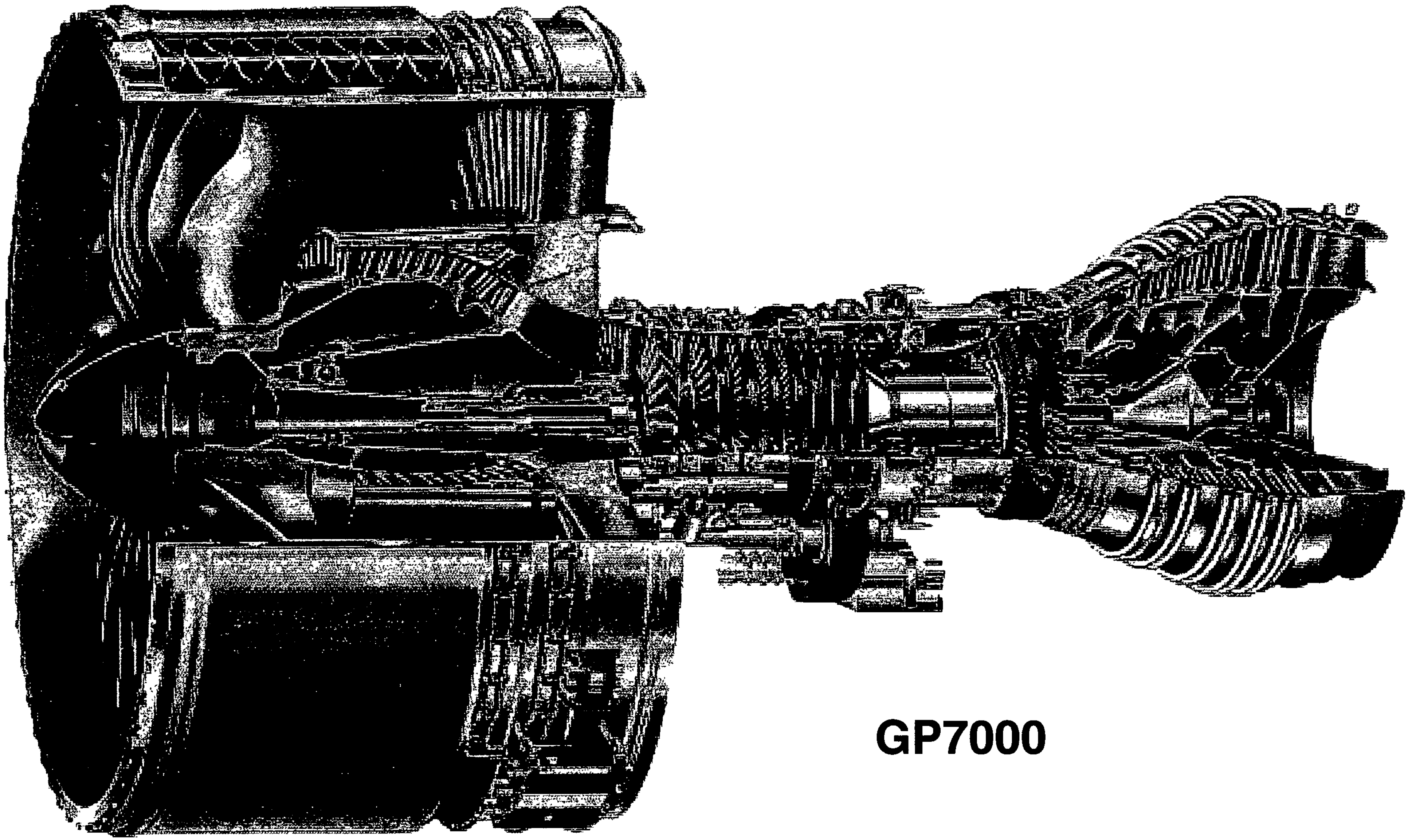
TURBINE BRANCH

at Lewis Field

CFM56-7



61" fan diameter
3-stage, 3-D Aero design booster
24 solid titanium wide-chord fan blades
FADEC II control
Titanium fan frame
9-stage, 3-D Aero compressor
3-D single crystal N5 turbine airfoils
4-stage, 3-D Aero LPT
Improves maintainability and performance
Retains
• Basic CFM56 architecture
• Low deterioration



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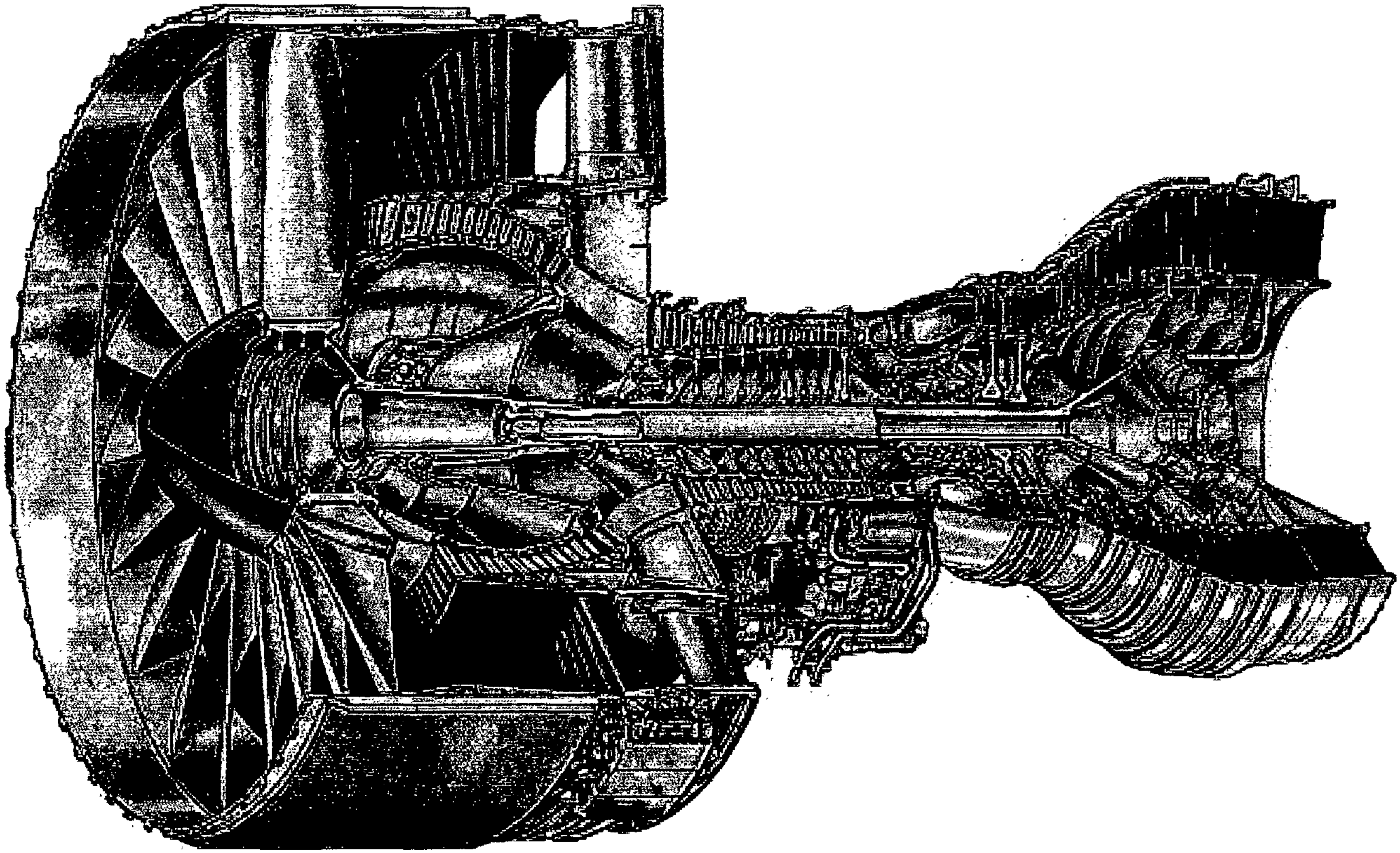
TURBINE BRANCH

at Lewis Field



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UNITED TECHNOLOGIES PRATT & WHITNEY

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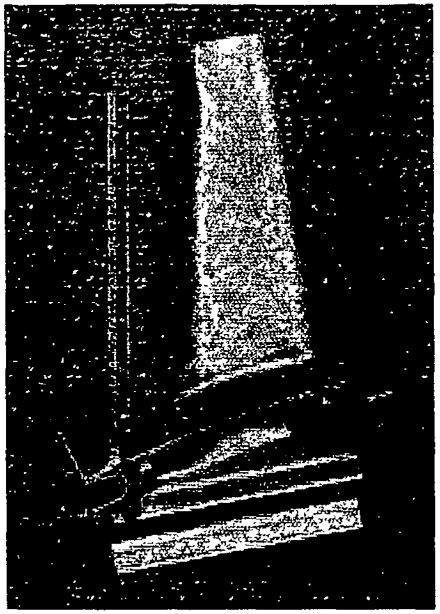
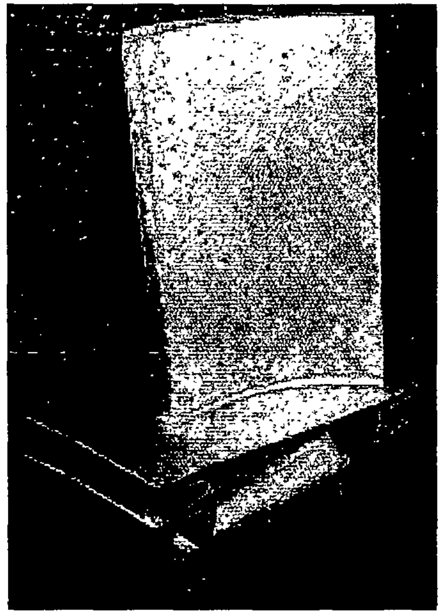
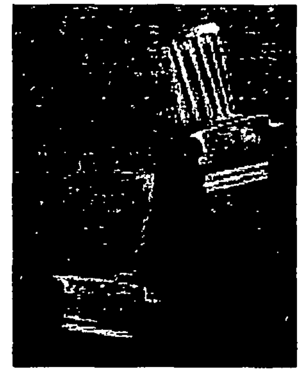
TURBINE BRANCH

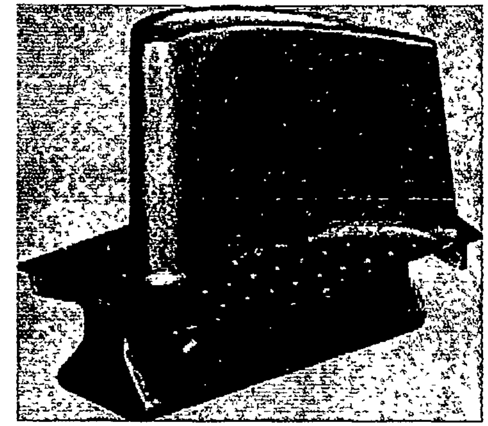
at Lewis Field

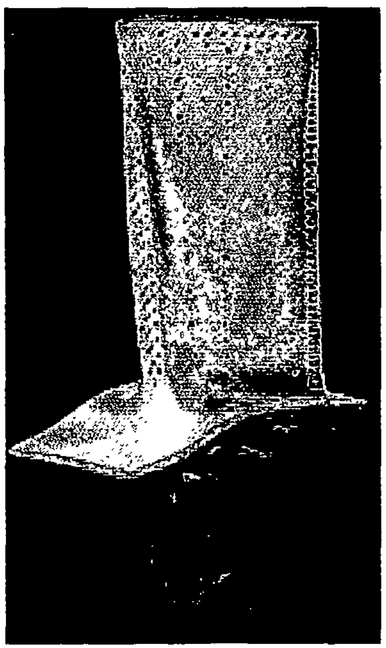
Some Typical Modern Cooled Turbine Blades

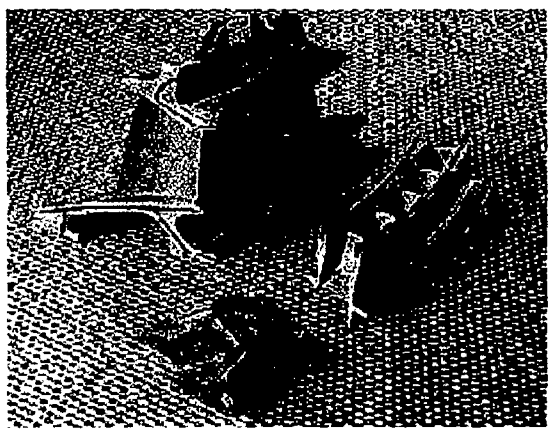


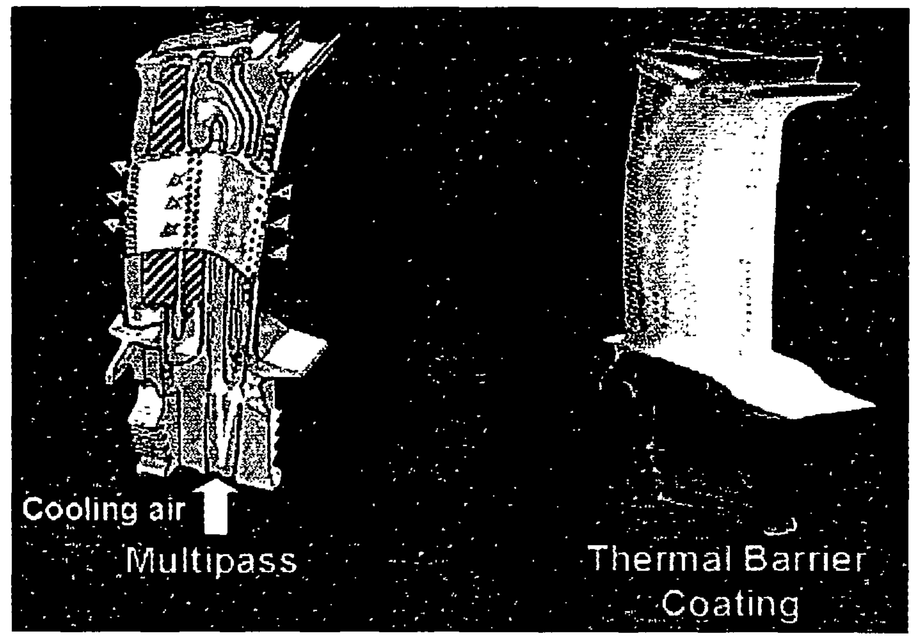








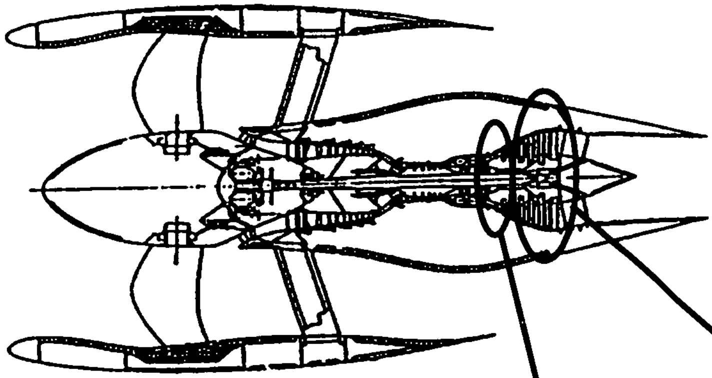




Aerodynamics & Heat Transfer Research for Turbines

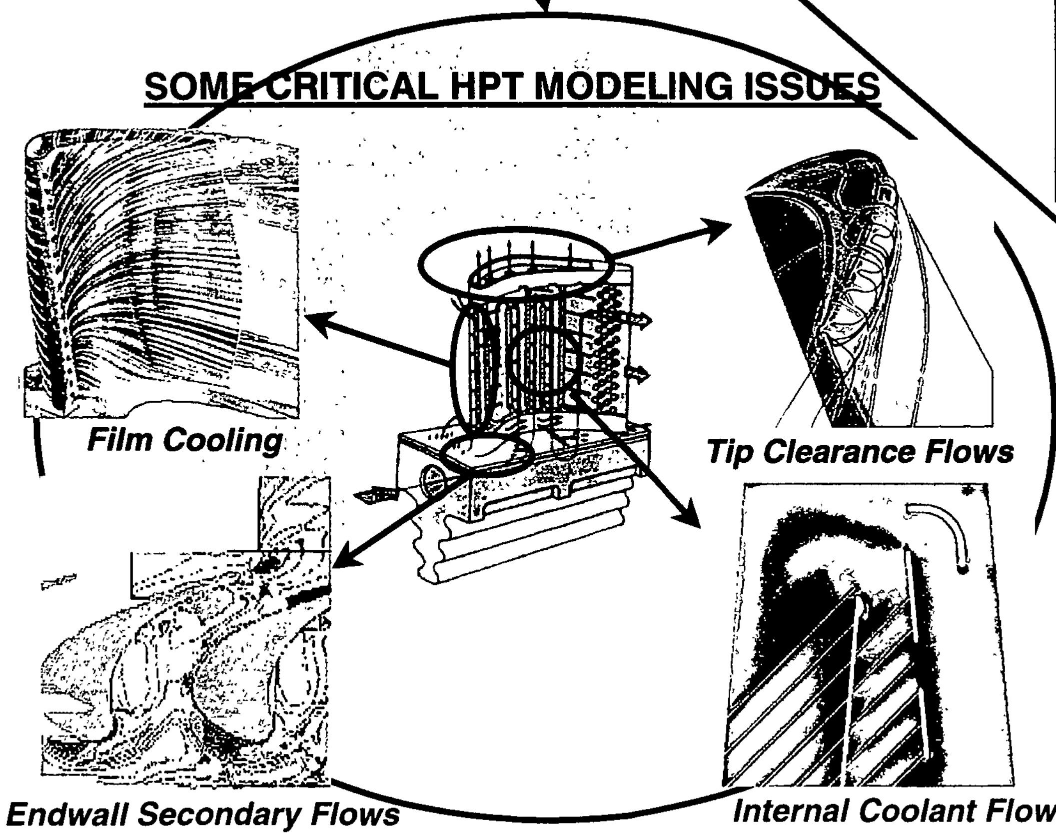
Experiments and Computations for:

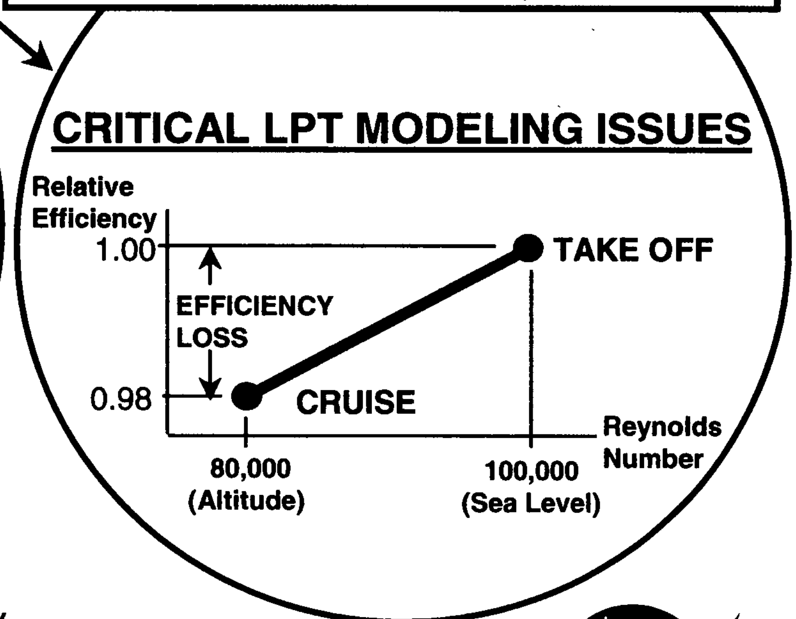
- **High-Pressure Turbine (HPT) -**
  Improved computational models for losses, heat transfer, and coolant flow.
- **Low-Pressure Turbine (LPT) -**
  Understand, model, and control the physical mechanisms responsible for high loss variations



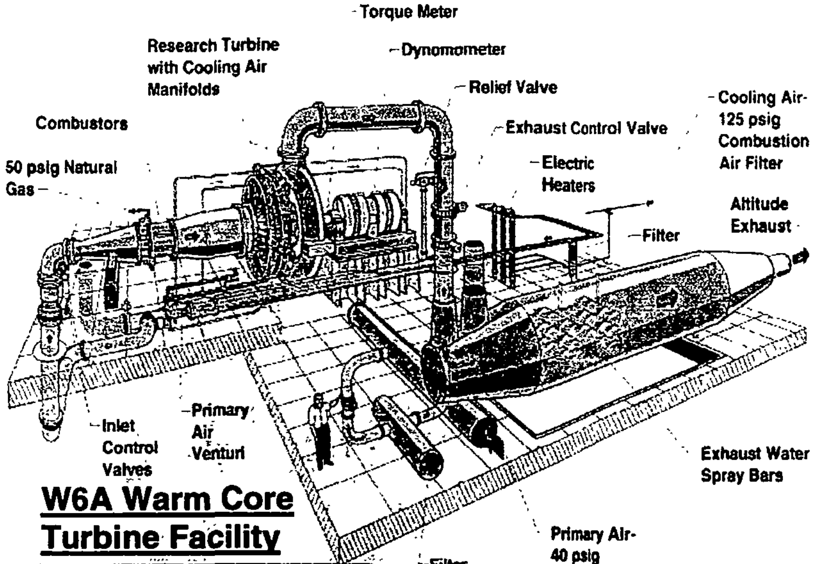
OUTCOME:

- **Reduced design cycle time & cost**
- **Improved component robustness & efficiency**

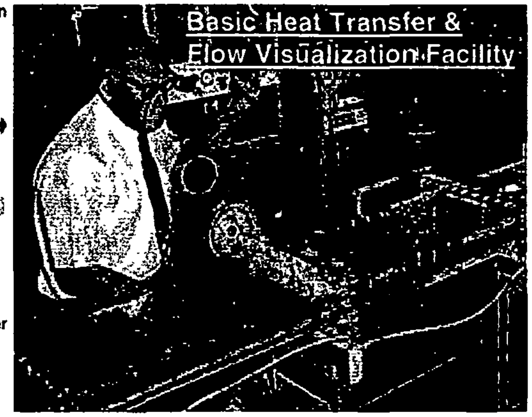




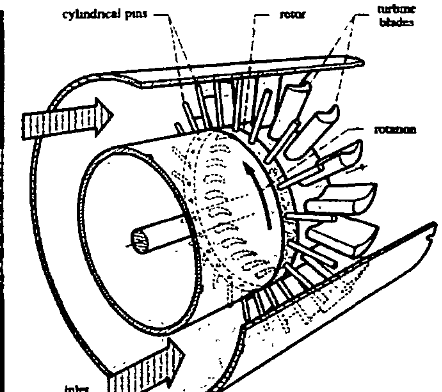
EXPERIMENTAL FACILITIES



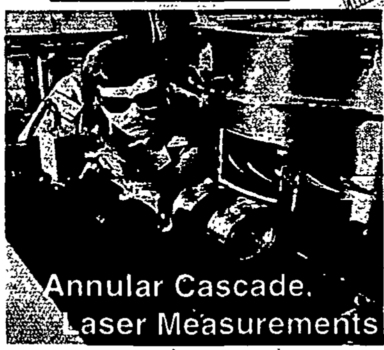
W6A Warm Core Turbine Facility



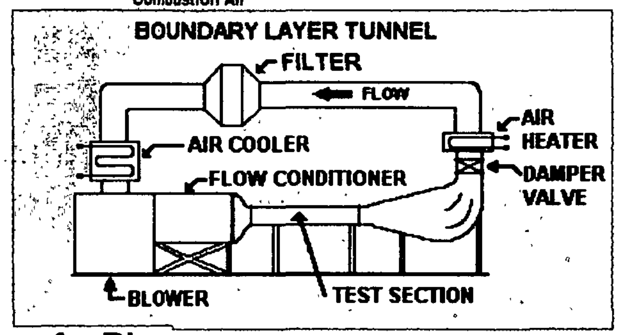
Basic Heat Transfer & Flow Visualization Facility



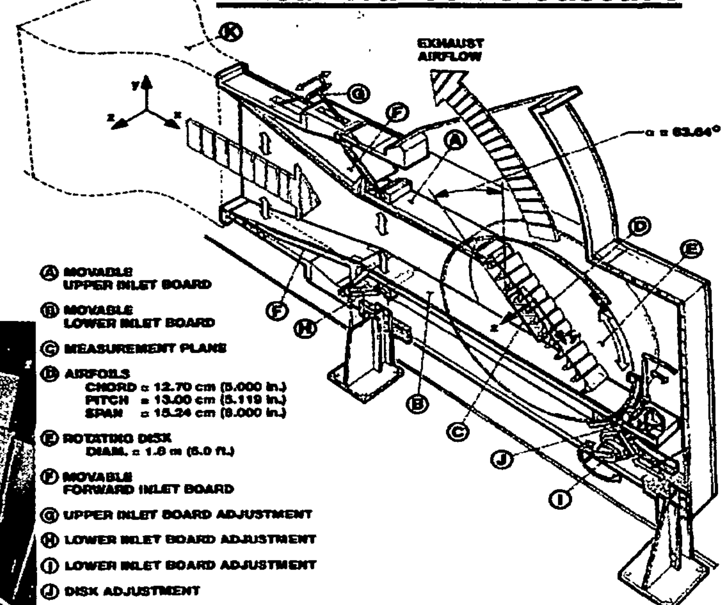
Rotor Wake Rig



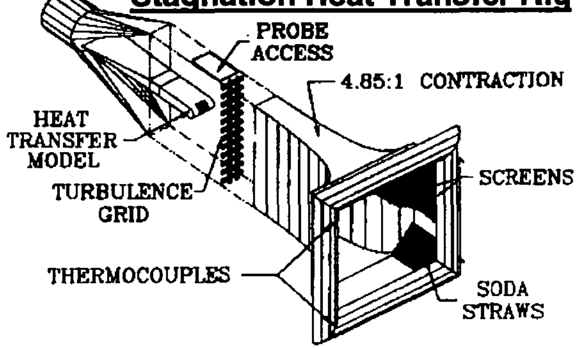
Annular Cascade, Laser Measurements

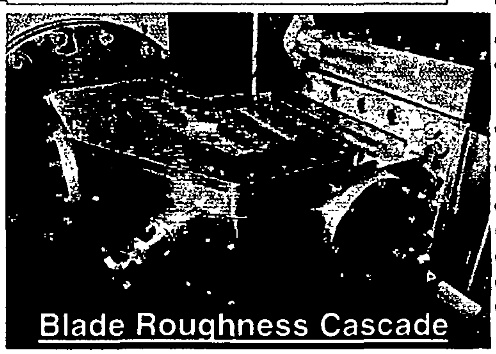


Linear Transonic Cascade



Stagnation Heat Transfer Rig





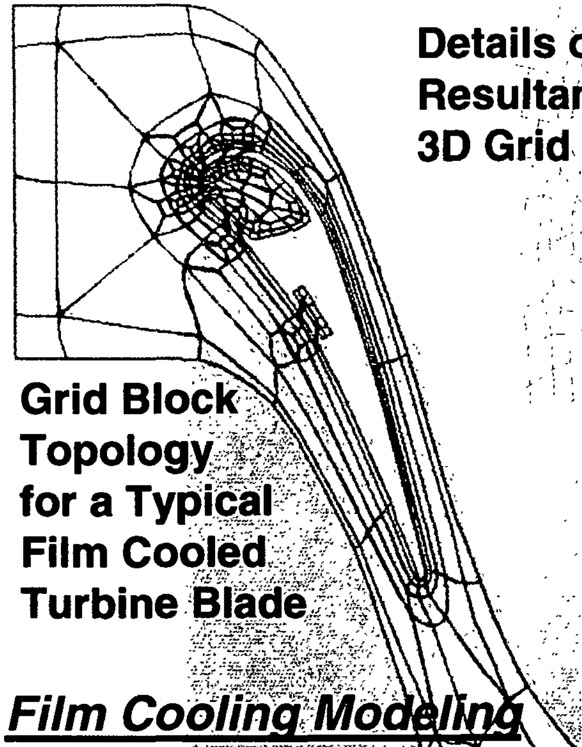
Blade Roughness Cascade

Glenn Research Center

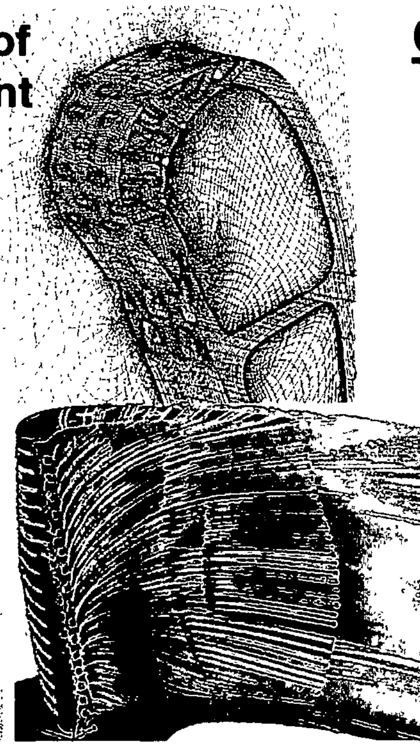
TURBINE BRANCH

at Lewis Field

COMPUTATIONAL MODELING with the Glenn-HT Code

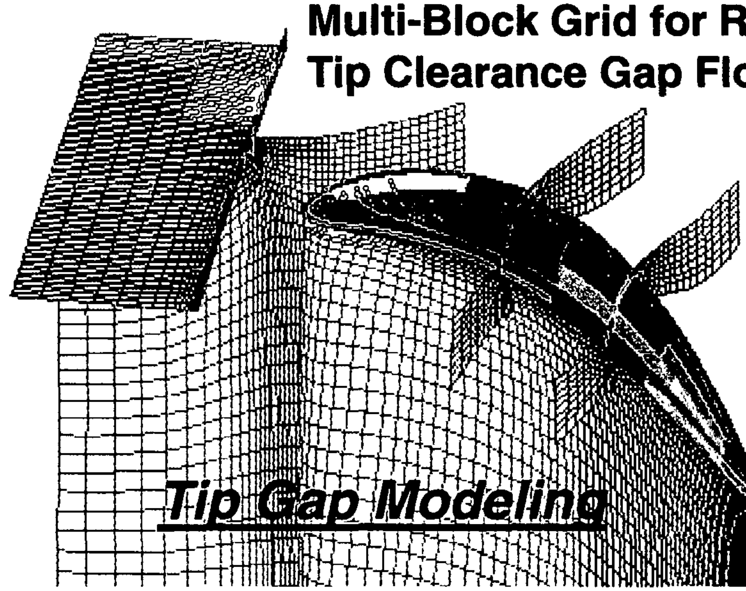


Grid Block Topology for a Typical Film Cooled Turbine Blade



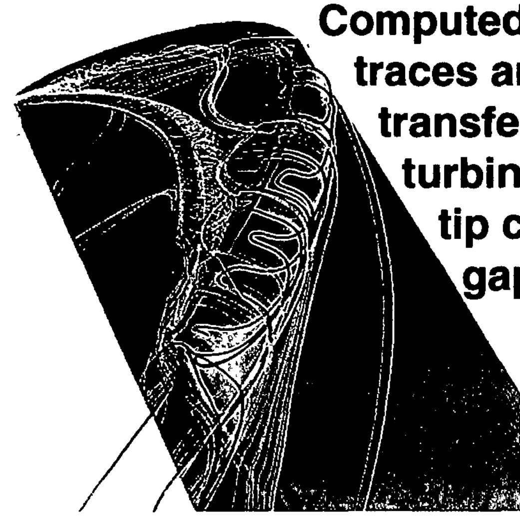
Details of Resultant 3D Grid

Film Cooling Modeling

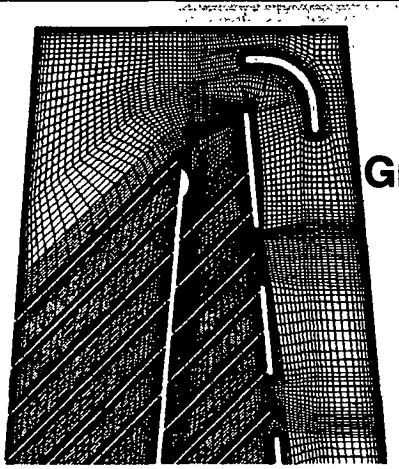


Multi-Block Grid for Rotor Tip Clearance Gap Flow

Tip Gap Modeling



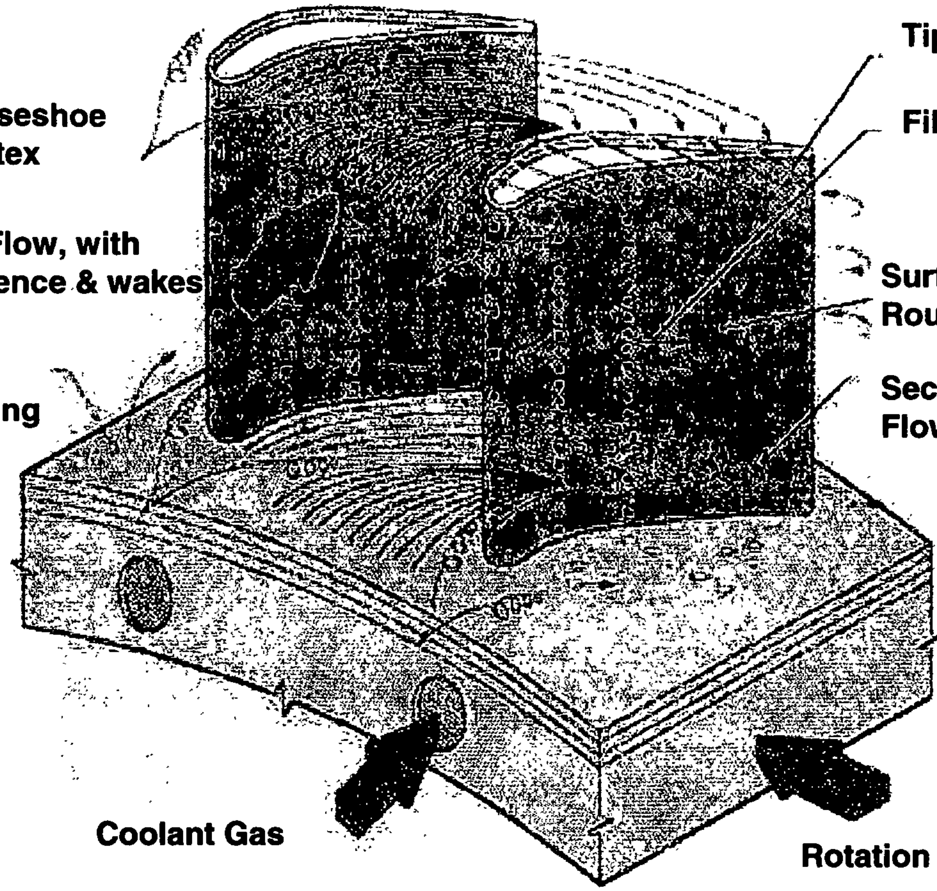
Computed flow traces and heat transfer in a turbine rotor tip clearance gap

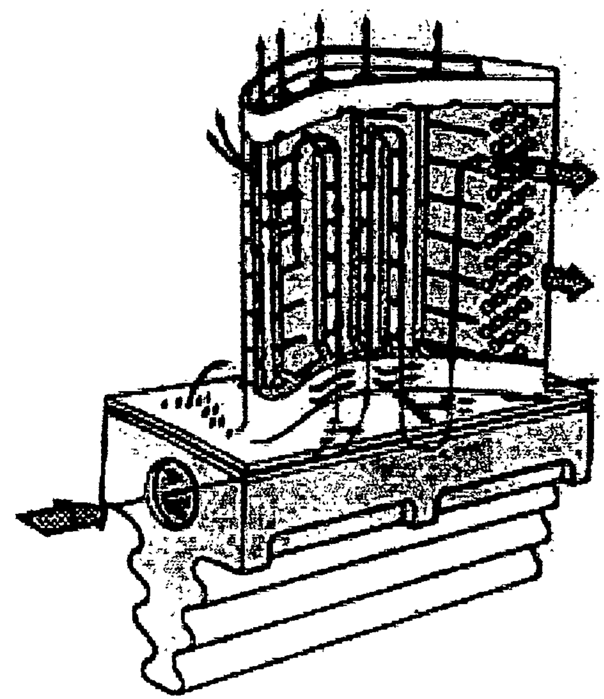


Grid

Glenn-HT Computed Heat Transfer

Internal Coolant Passage Modeling



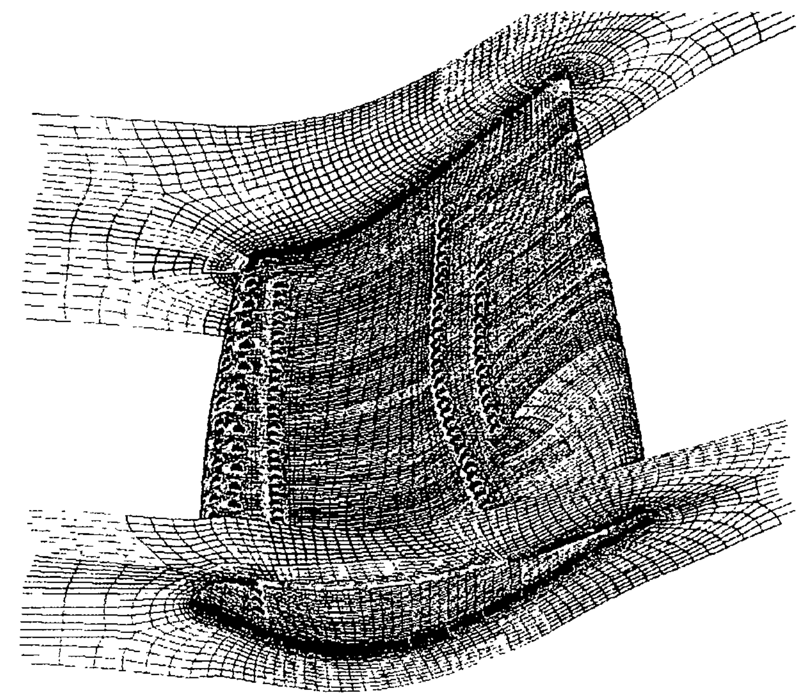


Turbine Blade Flow Phenomena to be Modeled

Glenn-HT: The NASA Glenn Research Center General Multi-Block Navier-Stokes Heat Transfer Code

Background

- Late 1980's, Robert Boyle at NASA Lewis developed near-wall Navier-Stokes CFD tools for modeling heat transfer in the Chima code.
- Prof. A. Arnone (U. of Florence) developed Turbomachinery CFD code with improved grid, TRAF3D, while on sabbatical at NASA Lewis.
- Utility of code for convective heat transfer calculations recognized early, Boyle modeling added by A. Ameri & Arnone.
- Ameri & Arnone add 2-Equation Turbulence model.
- V. Garg adds film cooling modeling.
- E. Steinthorsson creates Multi-Block grid capability (TRAF3D-MB).
- D. Rigby adds internal cooling passage models.
- Originally a modeling research tool, evolved into a design analysis tool.
- Offered to the domestic Turbine Community for evaluation at the DOD/IHPTET 1998 Turbine Engine Technology Symposium, renamed Glenn-HT.



Sample Multi-Block Grid for a Film-Cooled Turbine Rotor Blade

Capabilities of Glenn-HT

Accurate, efficient 3D analysis of flow & heat transfer in turbomachinery

- **Multi-block grid systems for handling complex geometries.**
  - **Arbitrary index orientations & multiple patches on each grid face.**
  - **Globally unstructured assembly of blocks-**
    - **Great flexibility for modeling complex geometries.**
    - **Grid generation capability rivals unstructured grids.**

- **Locally structured (body fitted) grids-**
  - **Well suited for viscous, near-wall phenomena.**
  - **Simple array data structures.**

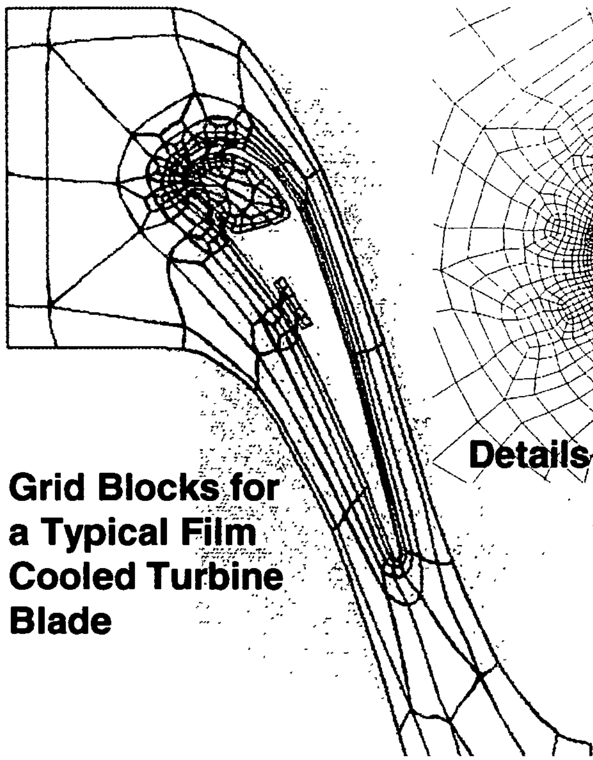
- **Block merging, using Rigby's Method of Weakest Descent (MWD), to reduce number of blocks & improve efficiency.**

- **Multi-grid convergence acceleration for computational efficiency**

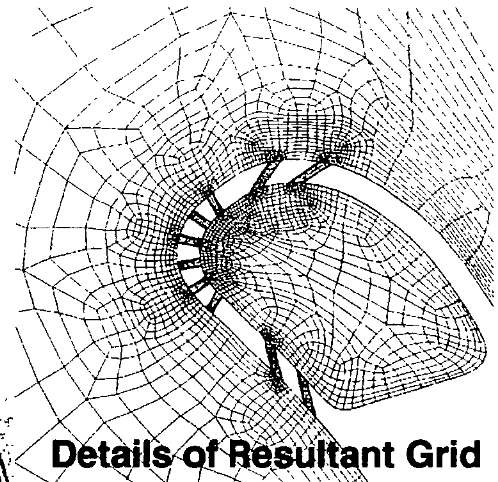
- **Finite-volume discretization for computational efficiency**

- **k-ω Turbulence model, no wall functions**

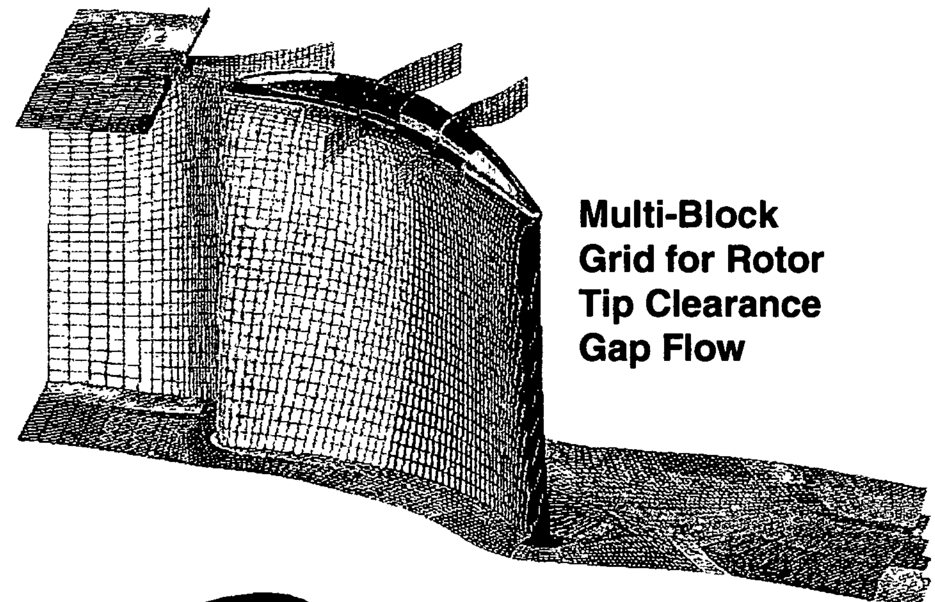
Multi-Block Grid Capability in the Glenn-HT 3-D Navier-Stokes Computer Code Allows Complex Turbomachinery Flow Field Details to be Modeled with a Structured Grid.



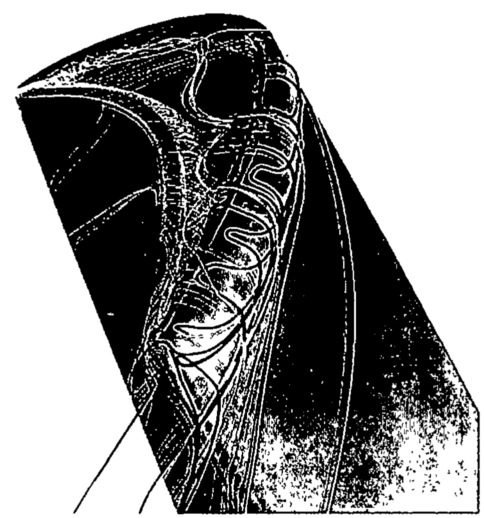
Grid Blocks for a Typical Film Cooled Turbine Blade



Details of Resultant Grid



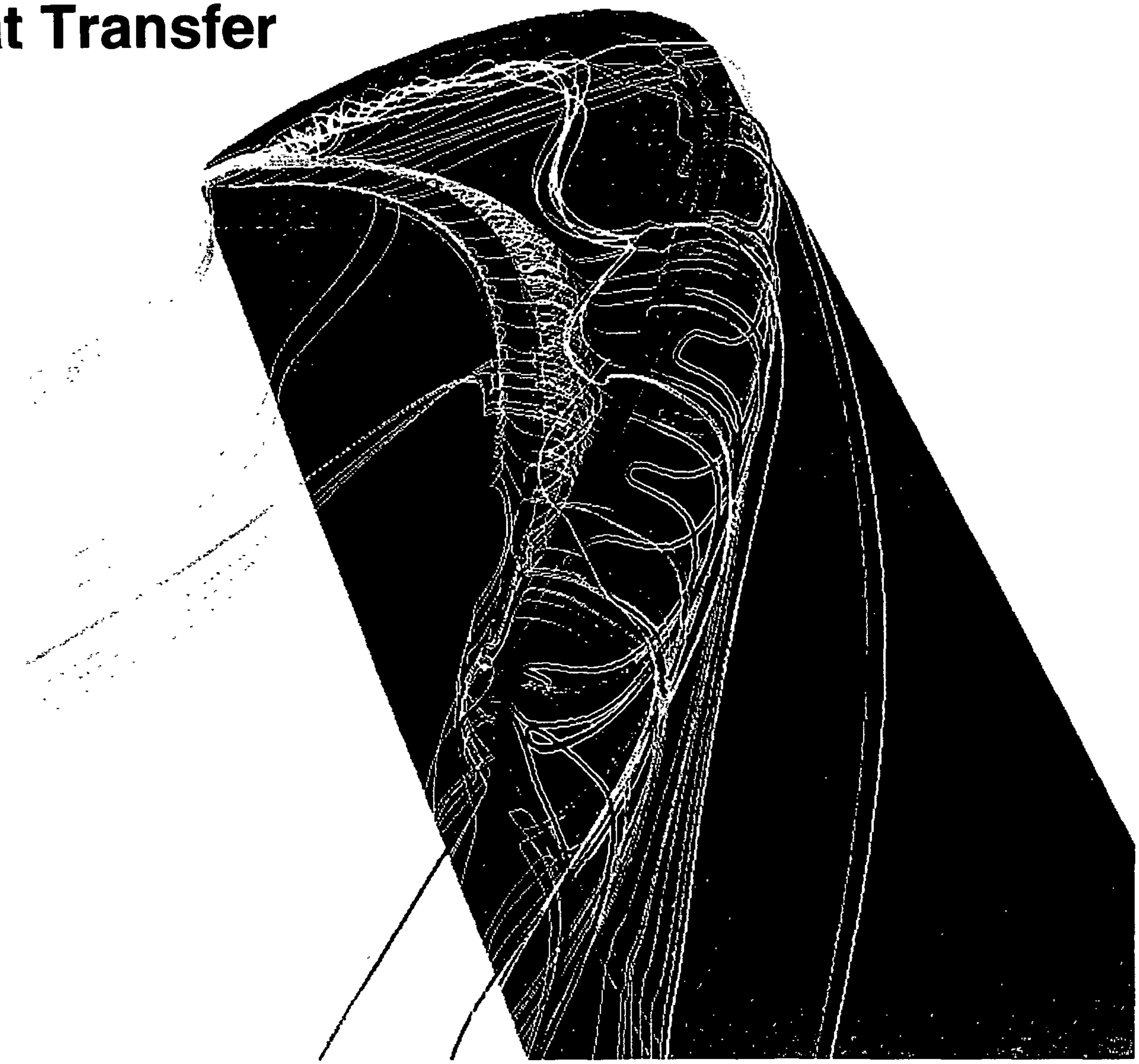
Multi-Block Grid for Rotor Tip Clearance Gap Flow



Computed flow traces in a turbine rotor tip clearance gap

- Multi-Block Topology results in the number of grid points reduced by an Order of Magnitude.
- Resulting grid can be concentrated in critical areas.

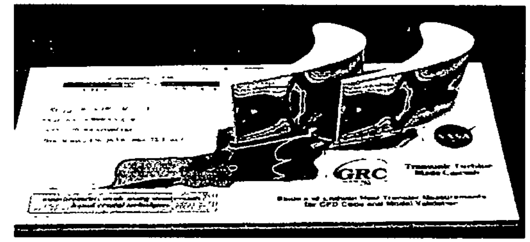
Glenn-HT Numerical Flow Visualization of Turbine Blade Tip Flow & Heat Transfer

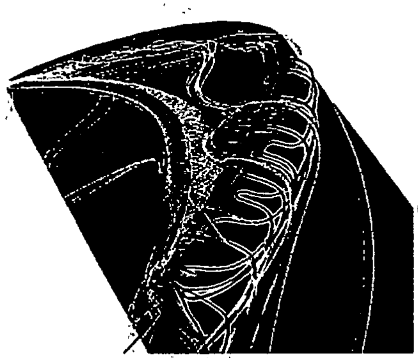


Glenn-HT: The NASA Glenn Research Center General Multi-Block Navier-Stokes Heat Transfer Code

Some Samples of the Range of Code Validation Cases:

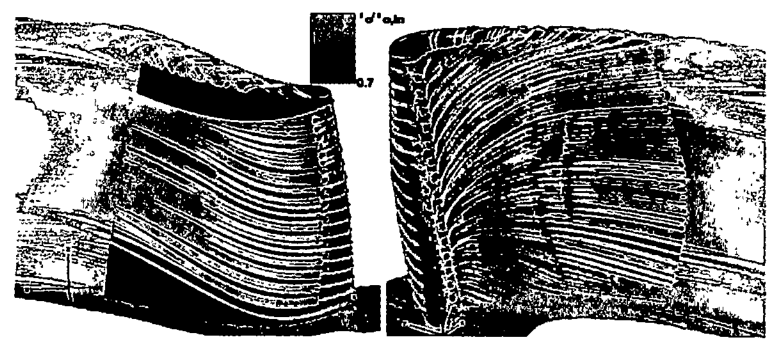
- **Heat Transfer in a Transonic Turbine Cascade**





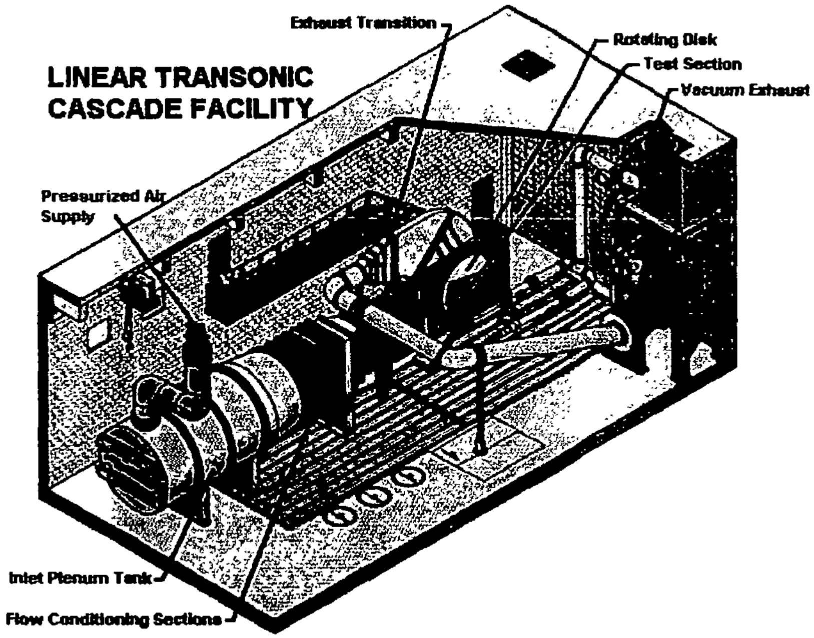
- **Turbine Tip Leakage Flow and Heat Transfer**

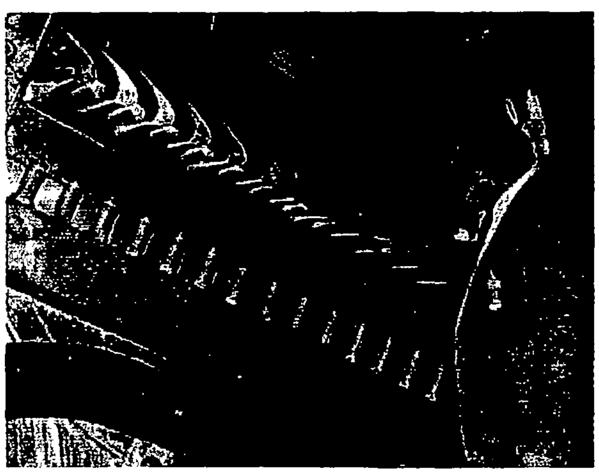
- **Analysis of Film Cooled Turbine Blade**

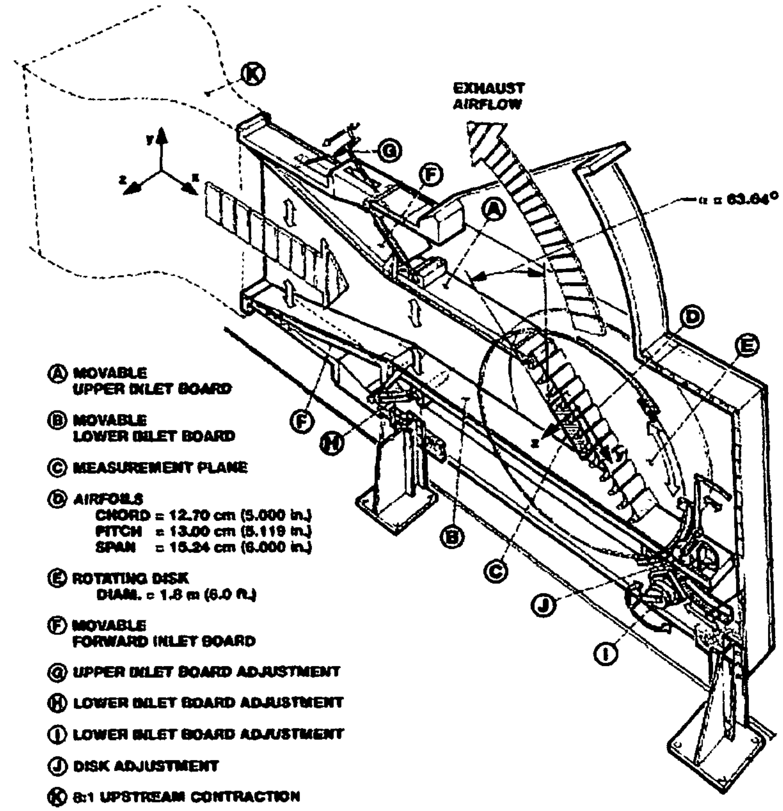


- **Turbine Internal Cooling Passage Analysis**

LINEAR TRANSONIC CASCADE FACILITY



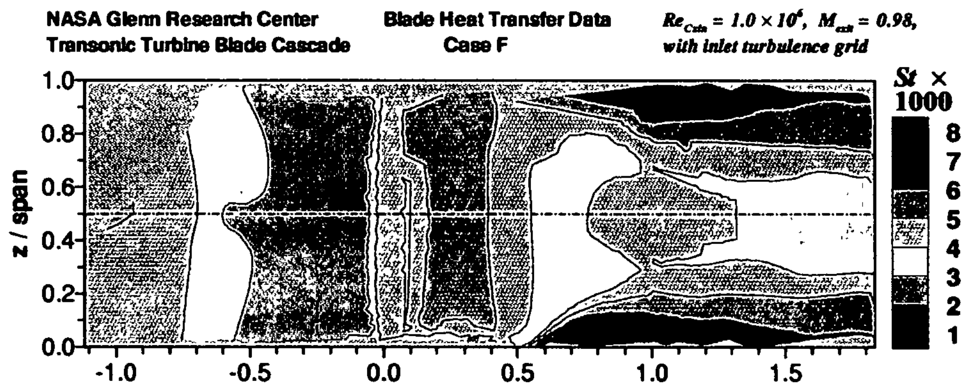


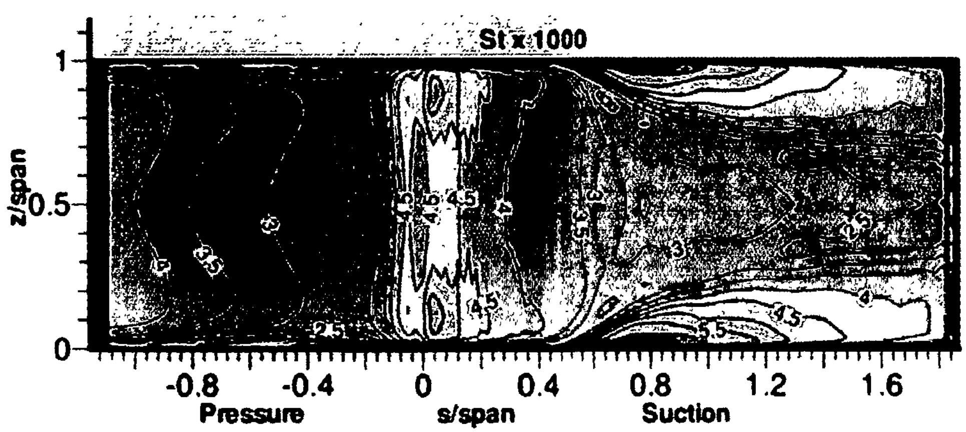


Exit Mach Number: Up to 1.33
Reynolds Number: 500,000 to 1,000,000
Inlet Angle Variable, -30º to +15º
Design Turning Angle: 136º

Glenn-HT Validation - Heat Transfer in a Transonic Turbine Cascade

Experimental Heat Transfer Data from NASA Glenn Transonic Turbine Cascade Rig





Glenn-HT Computed Heat Transfer, using the Shear Stress Transport (SST) Turbulence Model

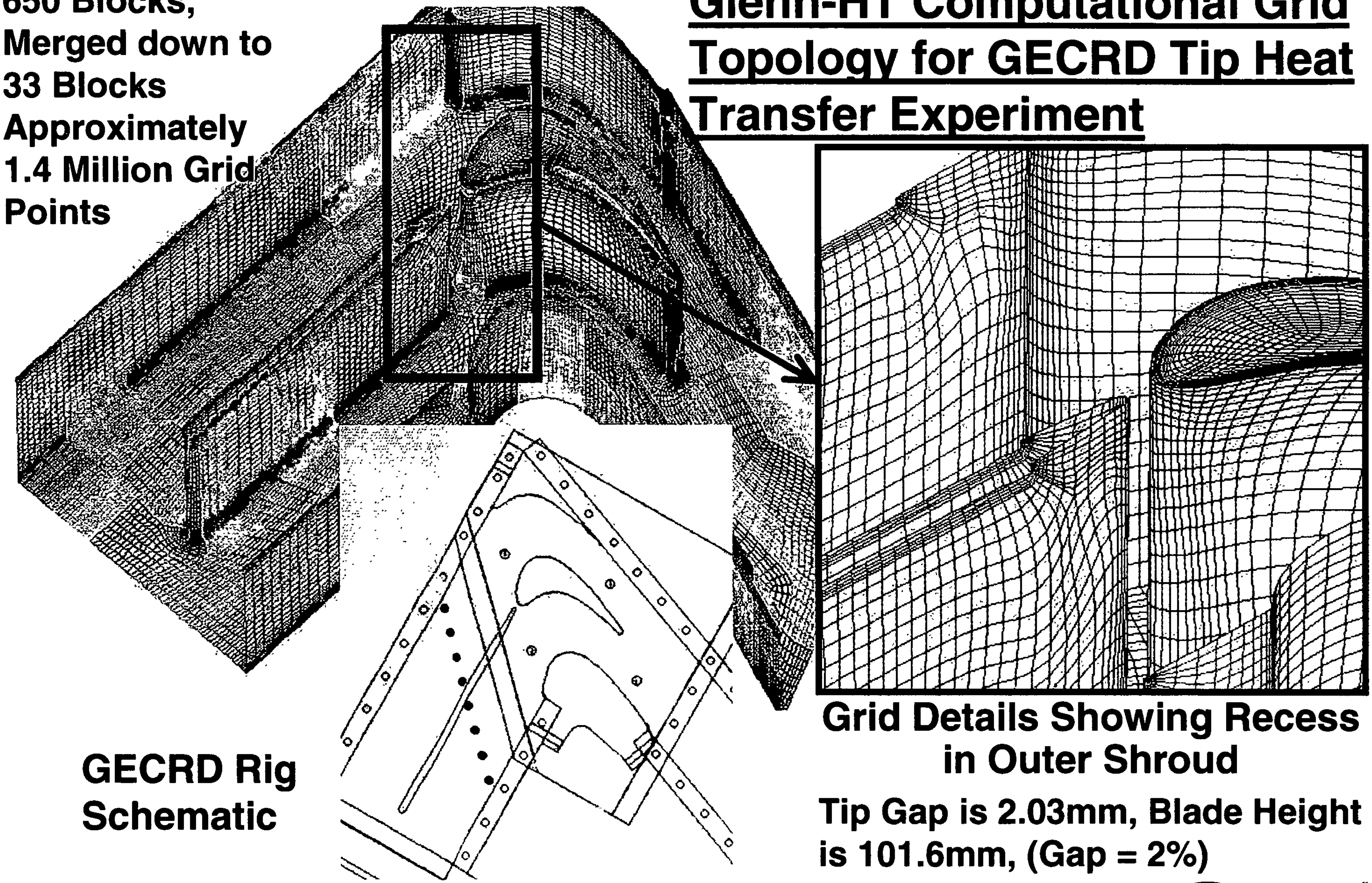
Glenn Research Center

TURBINE BRANCH

at Lewis Field

Glenn-HT Computational Grid Topology for GECRD Tip Heat Transfer Experiment

- 650 Blocks, Merged down to 33 Blocks
- Approximately 1.4 Million Grid Points



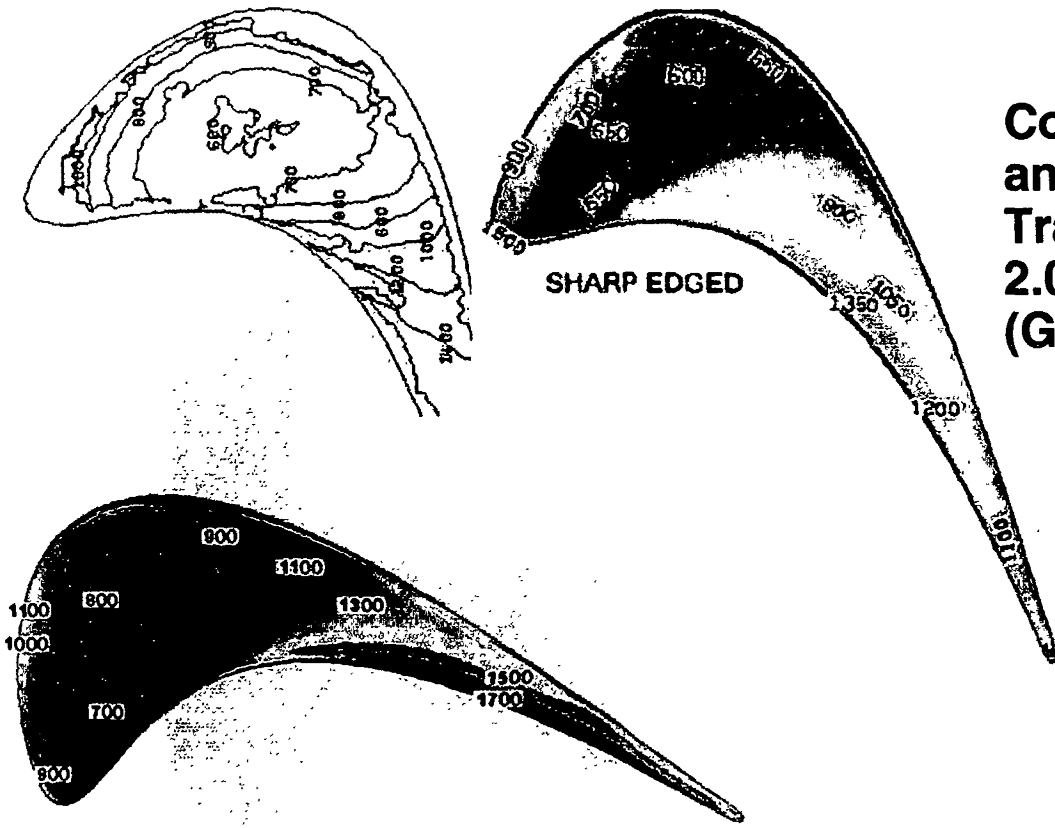
GECRD Rig Schematic

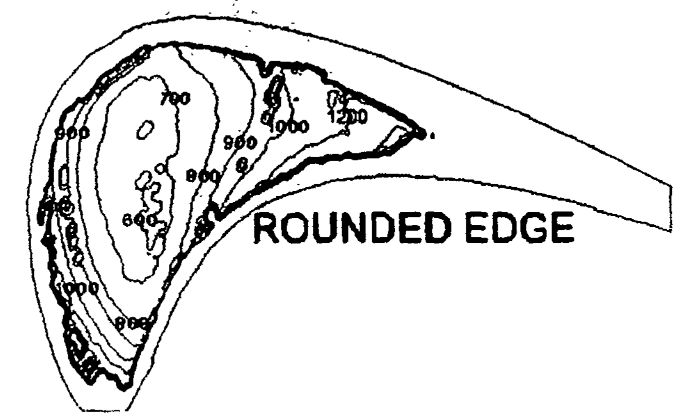
Grid Details Showing Recess in Outer Shroud

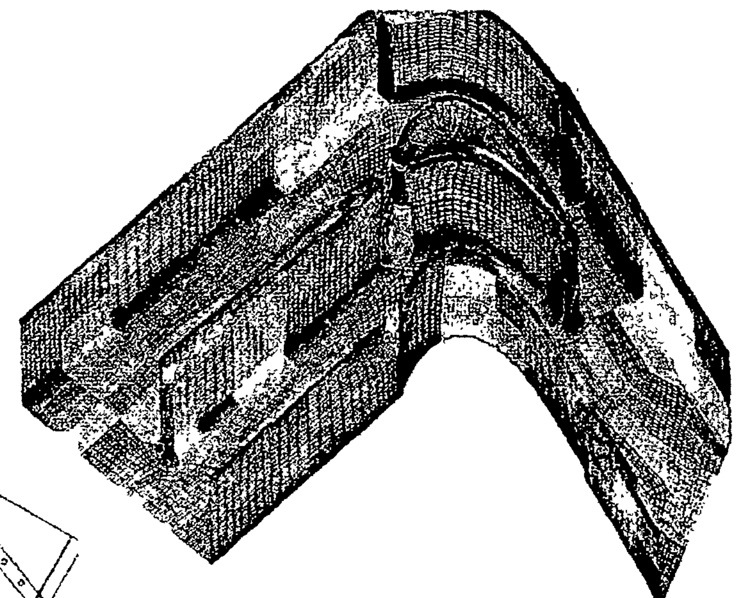
Tip Gap is 2.03mm, Blade Height is 101.6mm, (Gap = 2%)

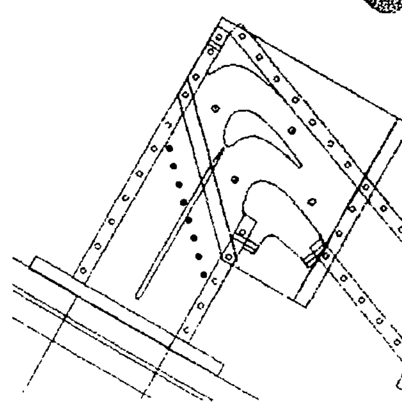
Blade Tip Heat Transfer

Comparison of GECRD Experiment and Glenn-HT Computation of Heat Transfer Coefficient. Tip Gap is 2.03mm, Blade Height is 101.6mm, (Gap = 2%)







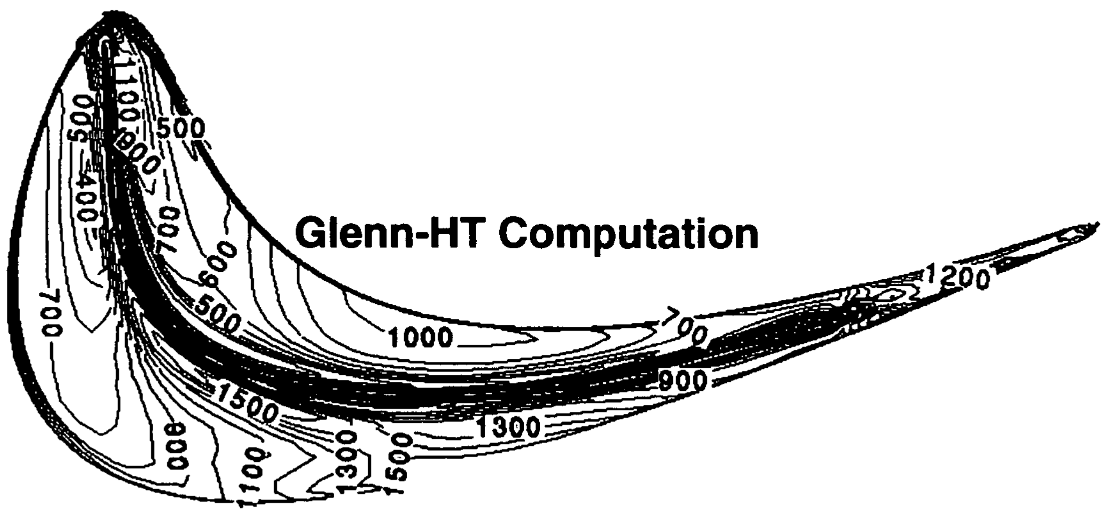


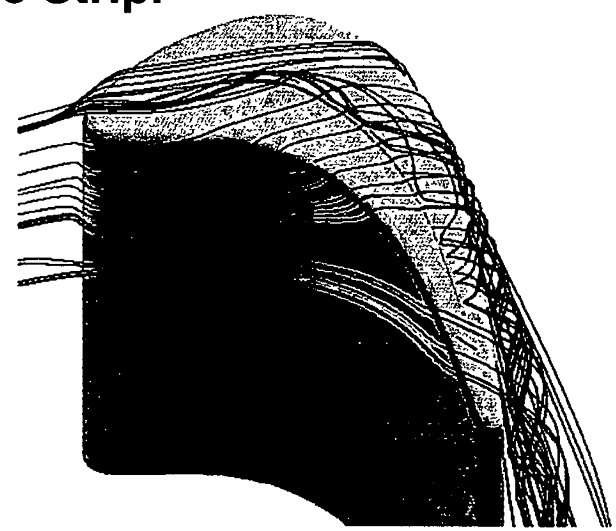
EXPERIMENTAL TEST SECTION

- **650 Blocks, Merged down to 33 Blocks**
- **Approximately 1.4 Million Grid Points**

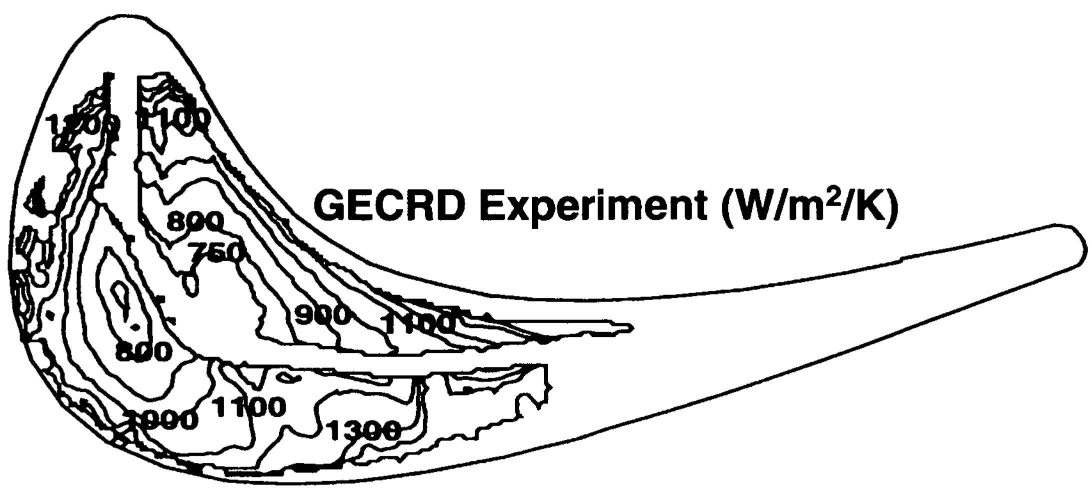
Blade Tip Heat Transfer

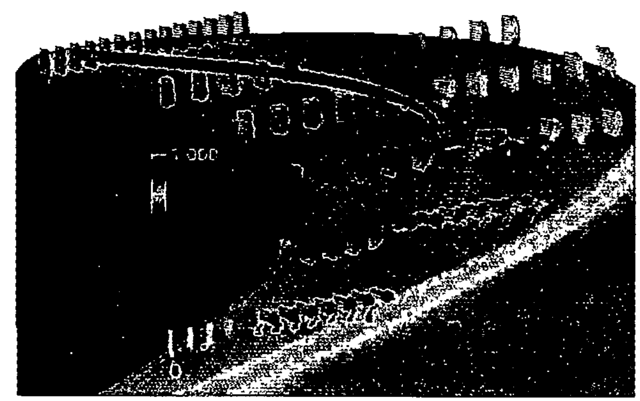
Comparison of Glenn-HT Computation and GECRD Experiment of Heat Transfer Coefficient over a Blade Tip with a Mean-Camberline Strip.





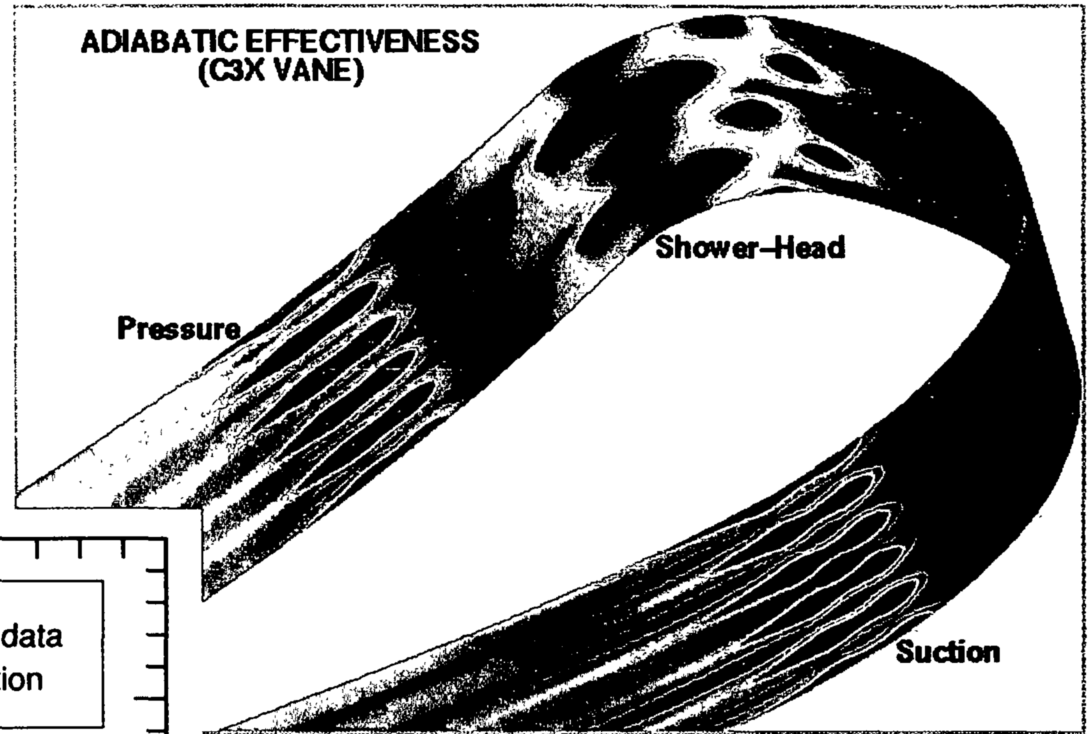
Computed Streamlines

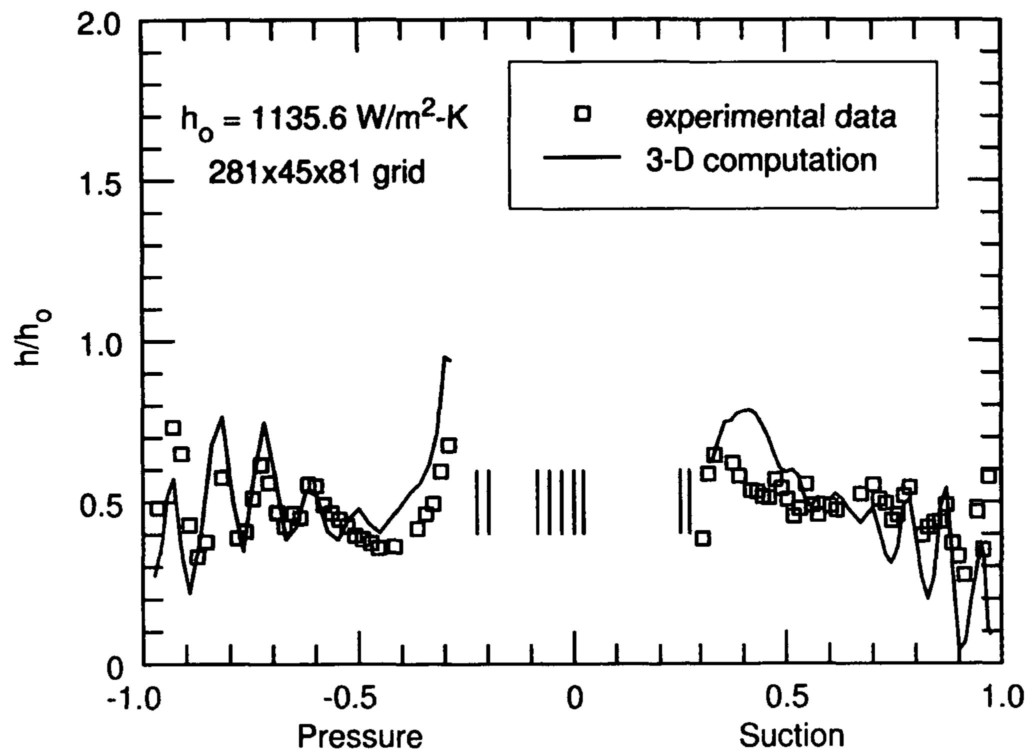




Computed Velocity Profiles

Heat Transfer in Film-Cooled Turbine Blades

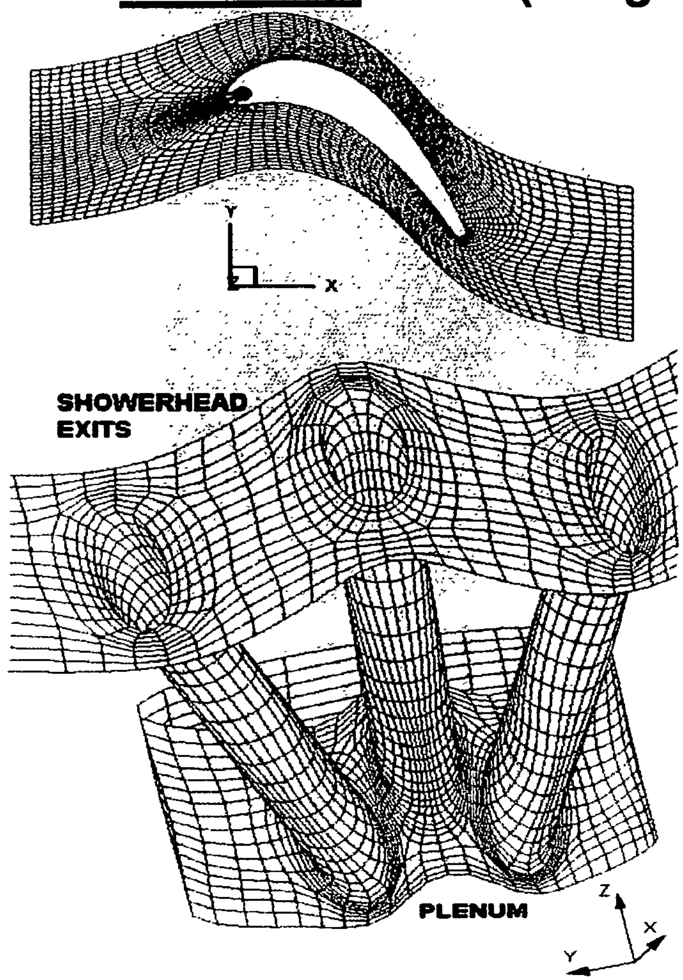


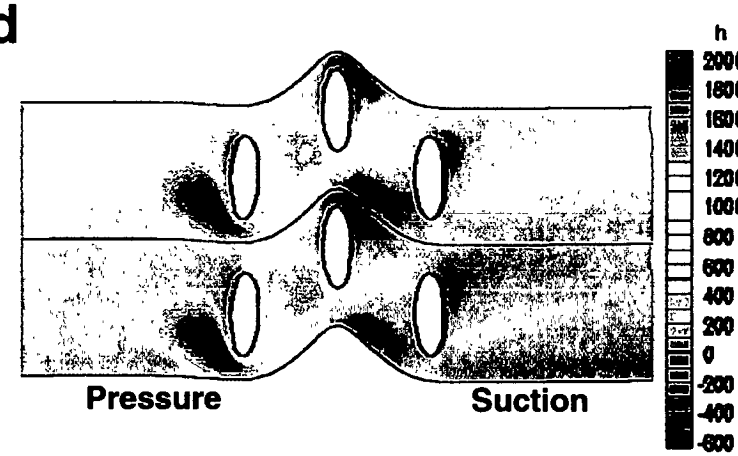


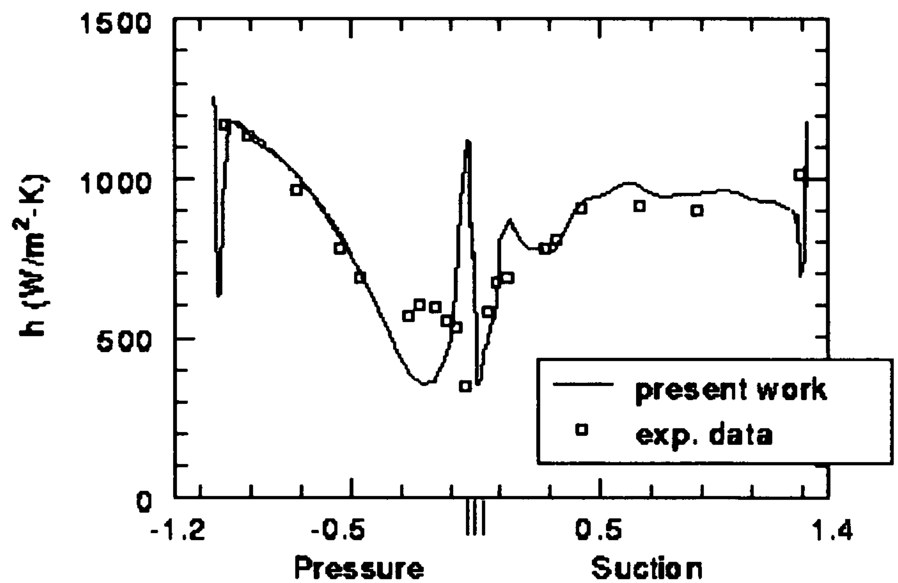
Comparison of measured mid-span heat transfer coefficient on the Allison C3X vane (Hylton et al, 1988) and Glenn-HT CFD results (Garg & Gaugler, 1994)

Heat Transfer in Film-Cooled Turbine Blades

Comparison of measured span-averaged heat transfer coefficient (Camci & Arts, VKI, 1985) and CFD computation using the Glenn-HT code (Garg & Rigby, 1998)

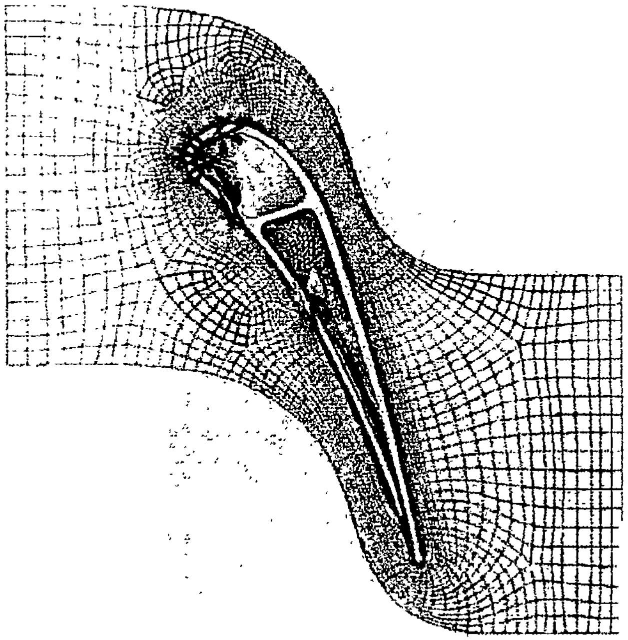


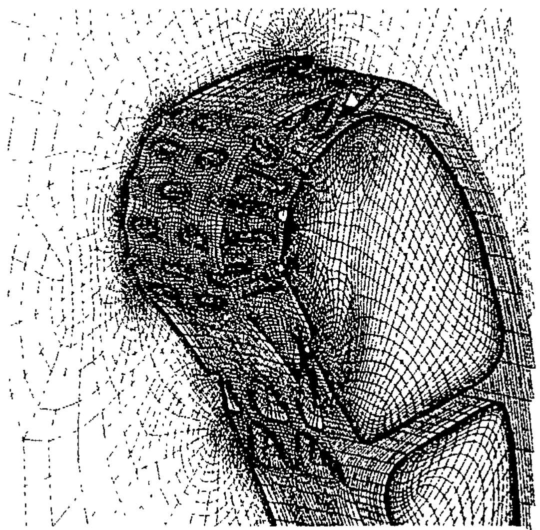




Case 154: M_{ex}= .905, $Re_{c,in}$= 8.42x10^5, T_o= 408.9 K T_w/T_o= 0.722, T_c/T_o= 0.52

Glenn-HT 3D Coupled Internal/External Simulation of a Film-Cooled Turbine Vane





Glenn-HT Predicted Wall Heat Flux on Plenum, Holes, & Vane

- Realistic film-cooled turbine vane
- Shaped & unshaped holes
- Holes supplied by two plena
- NASA GRC experiment planned
- Glenn-HT code used with 140 merged blocks
- Plena & film hole geometry fully modeled
- 2D design modeled as spanwise periodic

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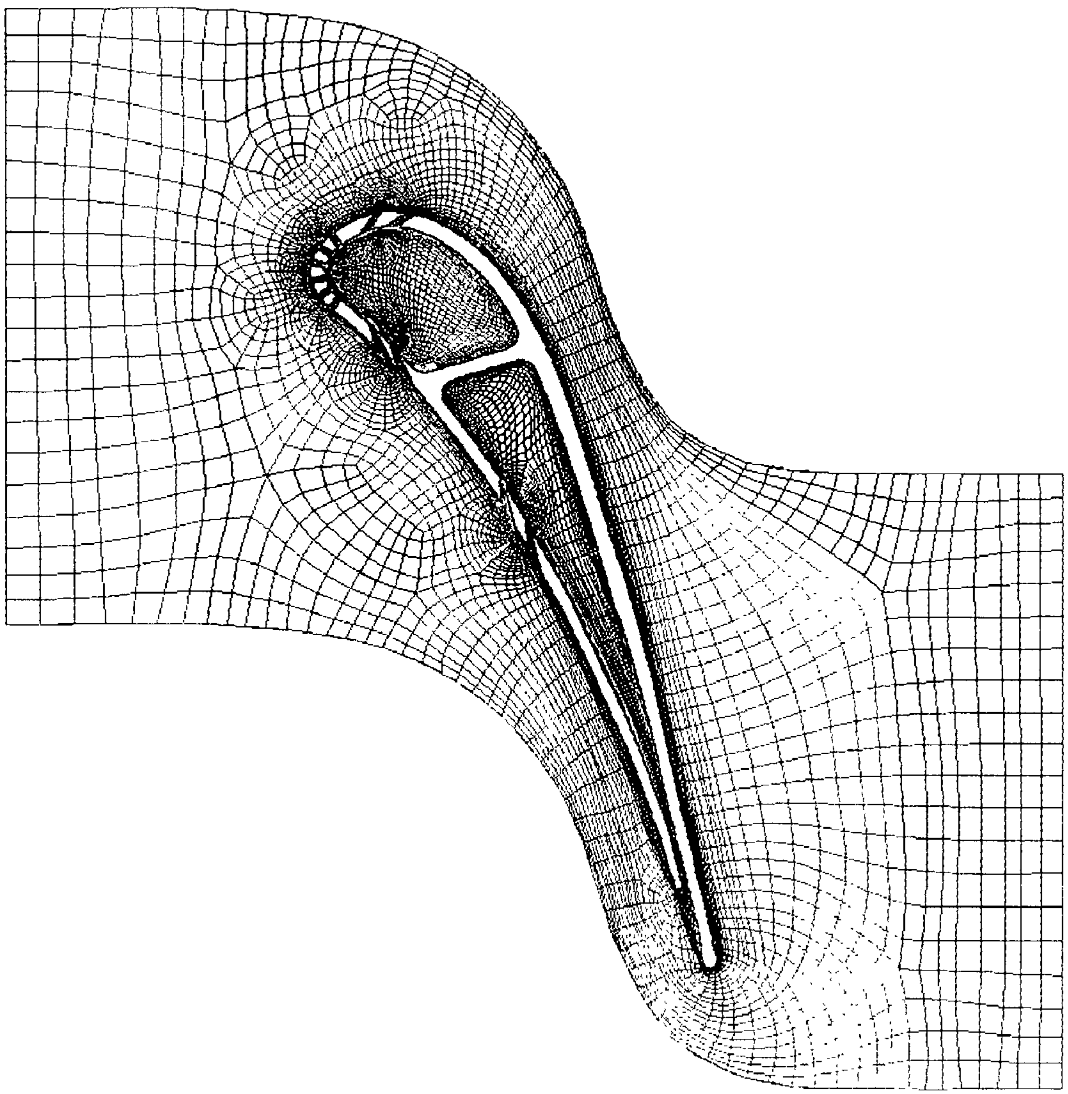

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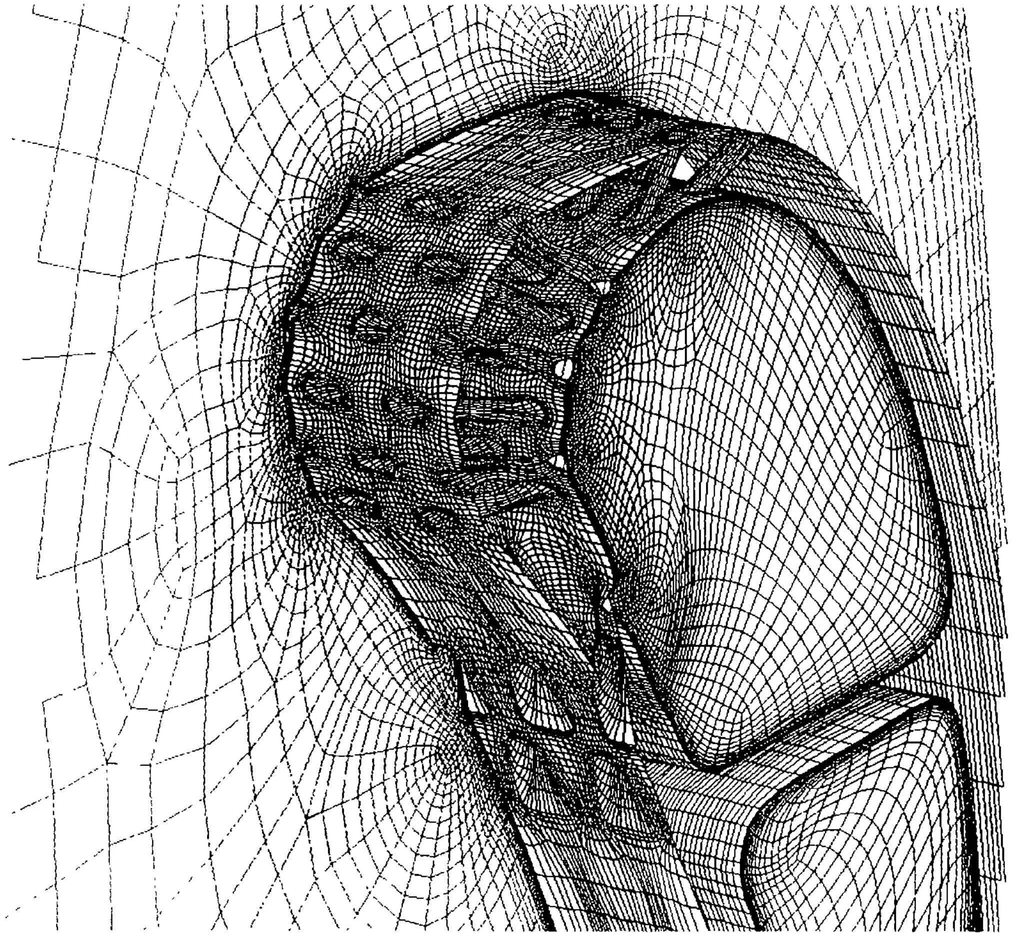
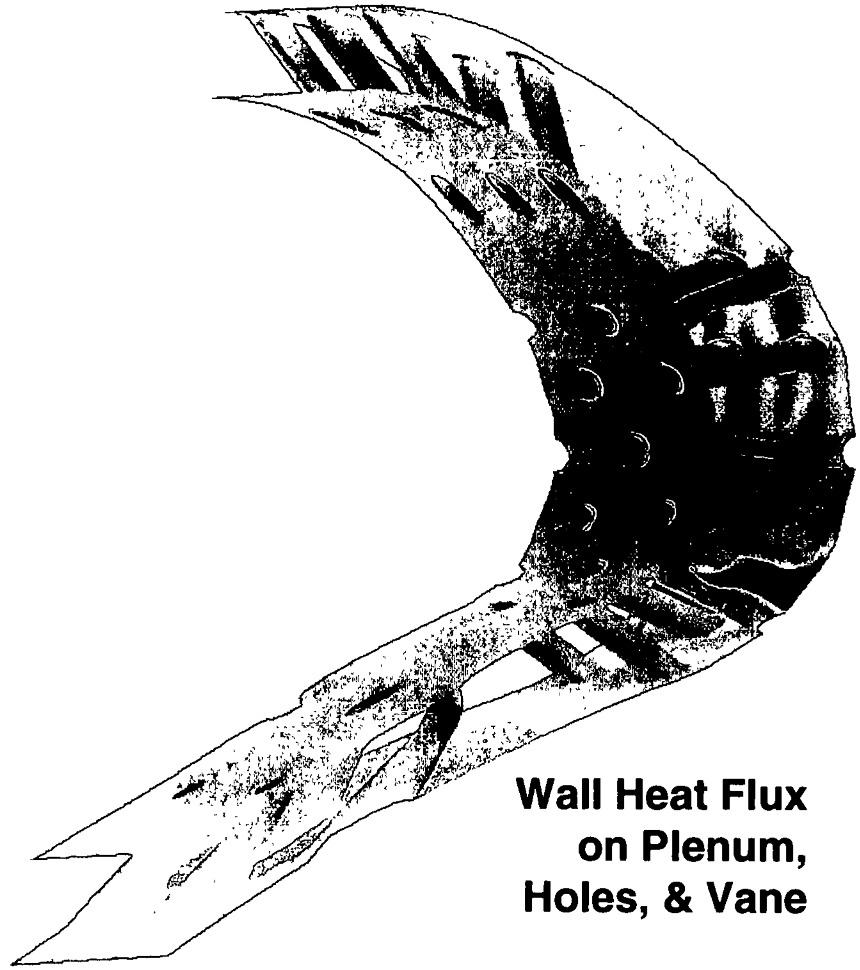
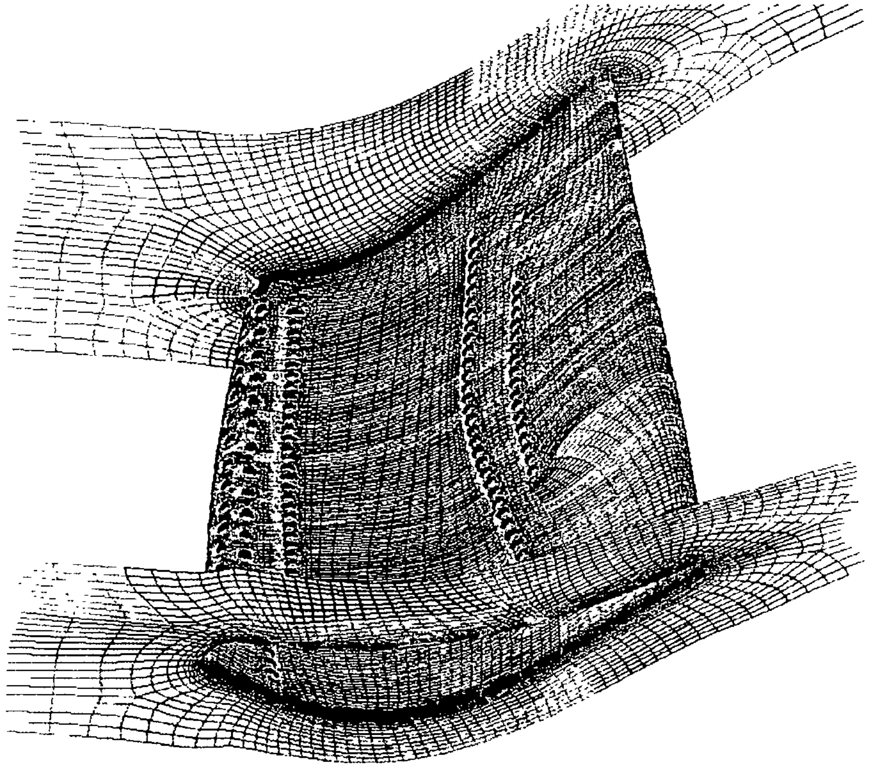


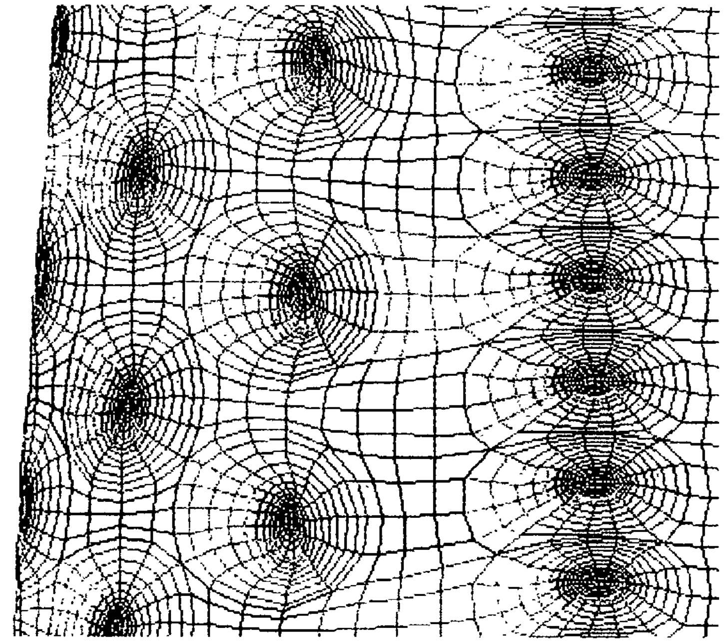


Wall Heat Flux
on Plenum,
Holes, & Vane

Glenn-HT Computation for a Film-Cooled Rotor Blade

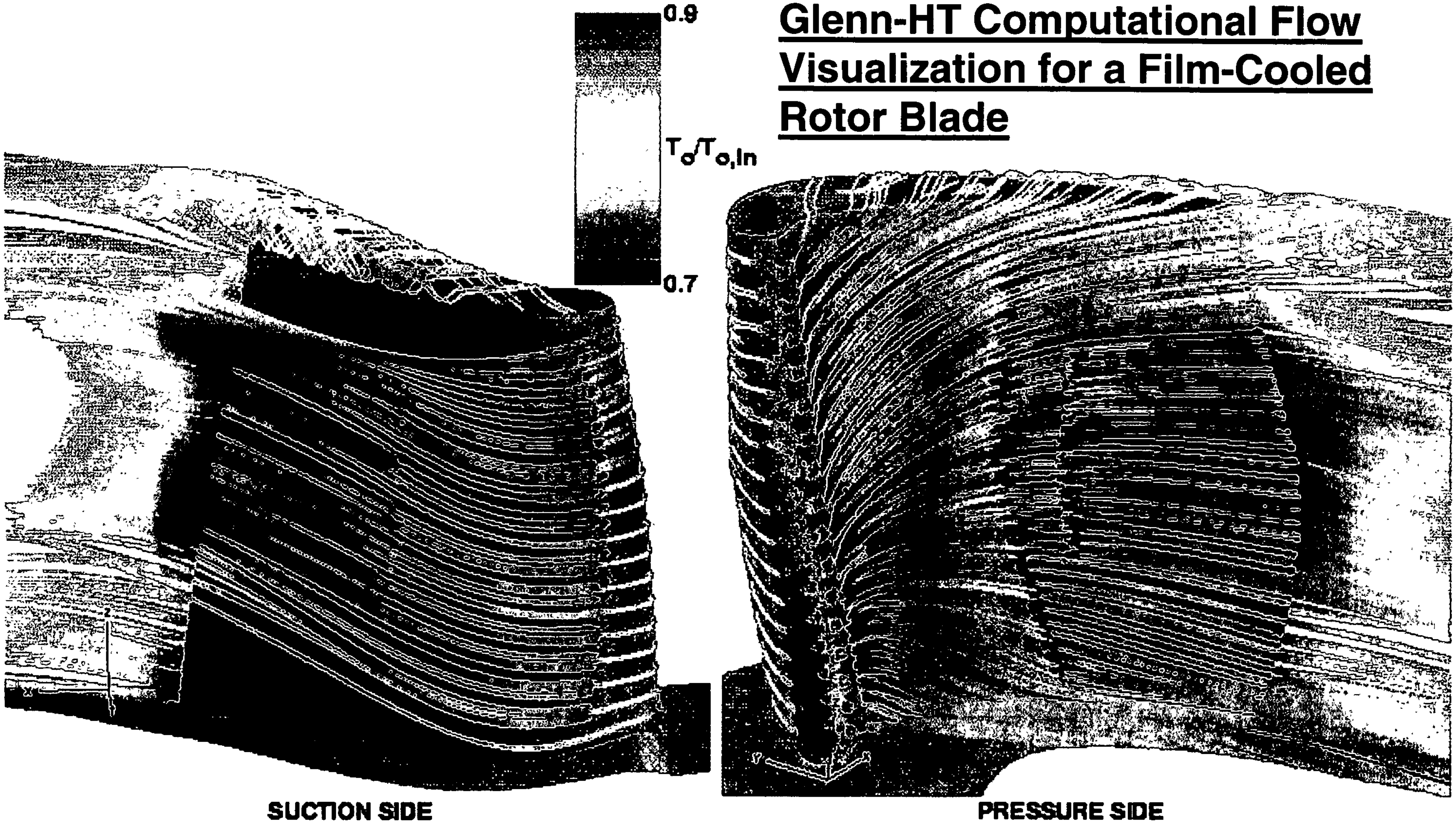


Grid details near holes



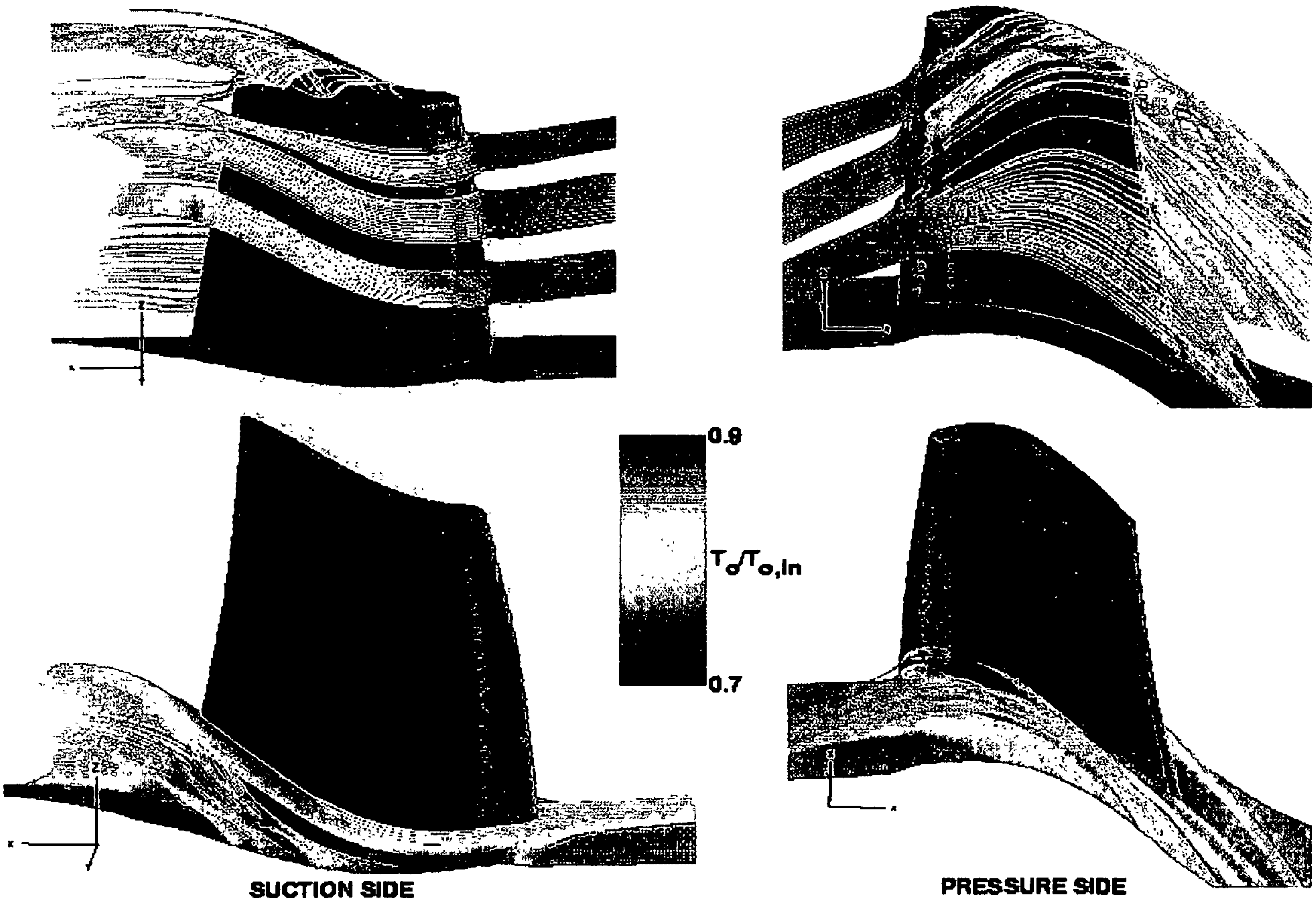
- Honeywell blade configuration, to be tested at OSU Turbine Lab.
- No span-wise symmetry, so all 172 holes must be gridded, as well as tip clearance gap.
- 80 cells over each hole exit, flow & turbulence boundary condition distributions specified for each hole.
- Over 2.2 million grid cells overall.

Glenn-HT Computational Flow Visualization for a Film-Cooled Rotor Blade



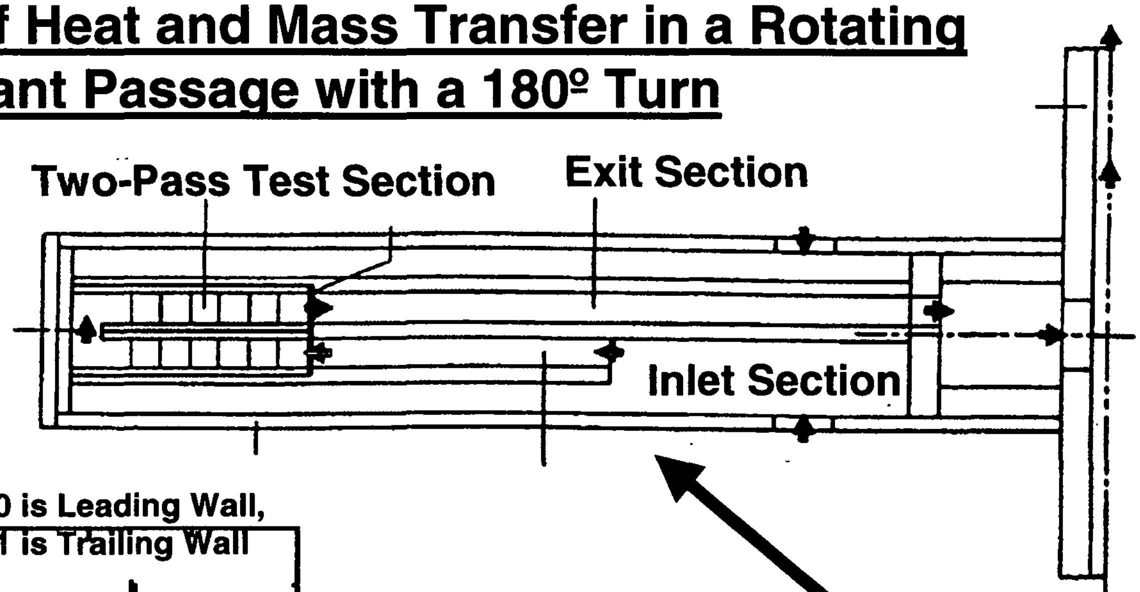
STREAMLINES, COLORED BY TEMPERATURE, EMANATING FROM HOLES OVER THE COOLED BLADE SURFACE WITH DISTRIBUTION OF h

Glenn-HT Computational Flow Visualization for a Film-Cooled Rotor Blade

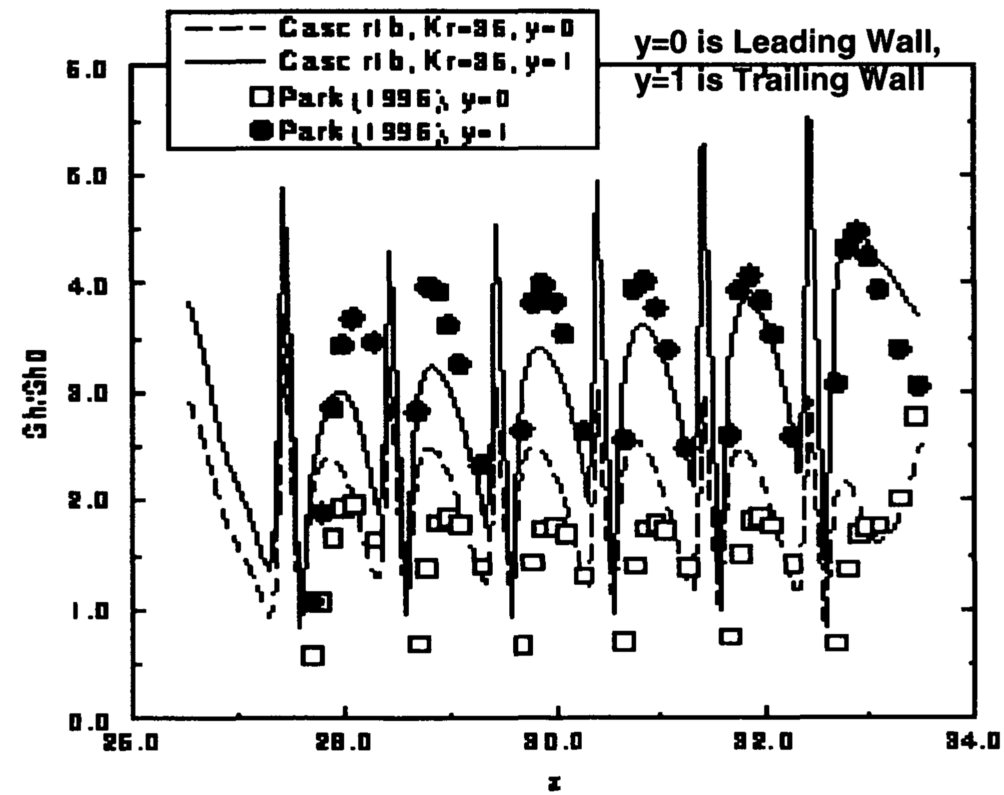


STREAMLINES, COLORED BY TEMPERATURE, OVER THE COOLED BLADE SURFACE WITH DISTRIBUTION OF h

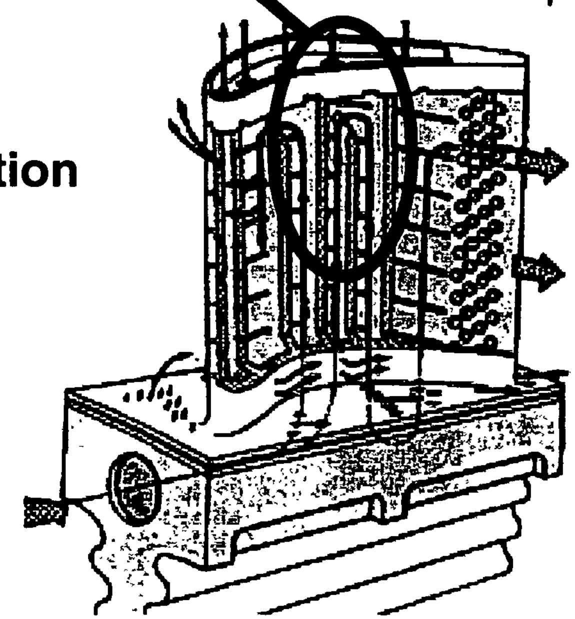
Glenn-HT Prediction of Heat and Mass Transfer in a Rotating Ribbed Coolant Passage with a 180º Turn



Experiment of Park et al (1996)



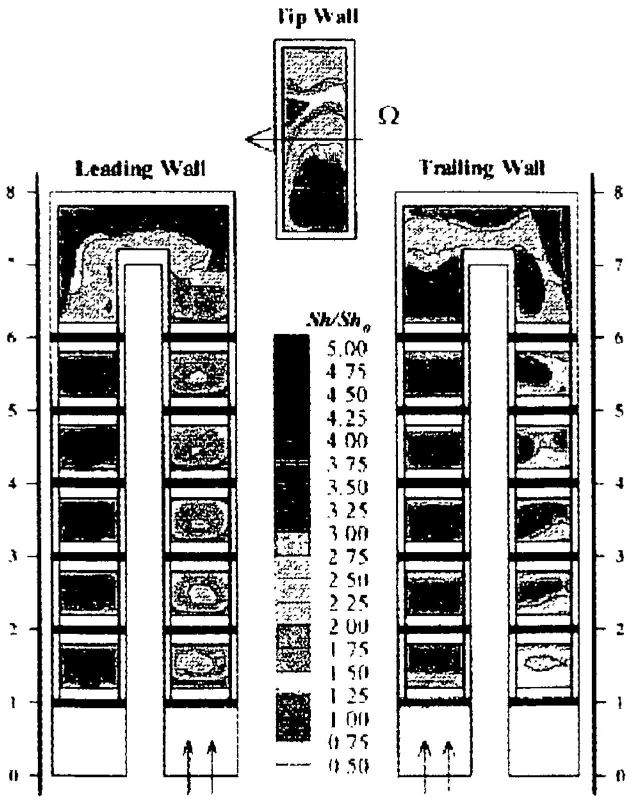
Glenn-HT Computation by Rigby, 1998



Glenn-HT Internal Cooling Passage Modeling

(Rotating Channel with 180^0 turn & ribs)

Normalized Sherwood No.



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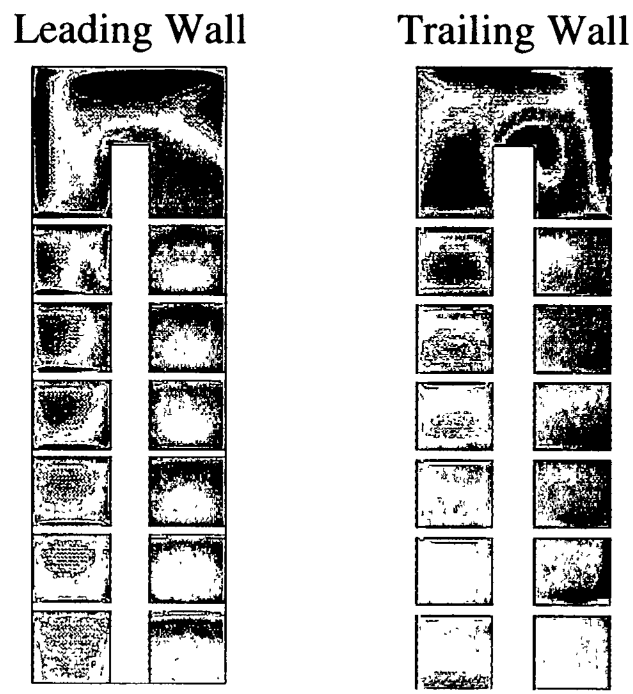


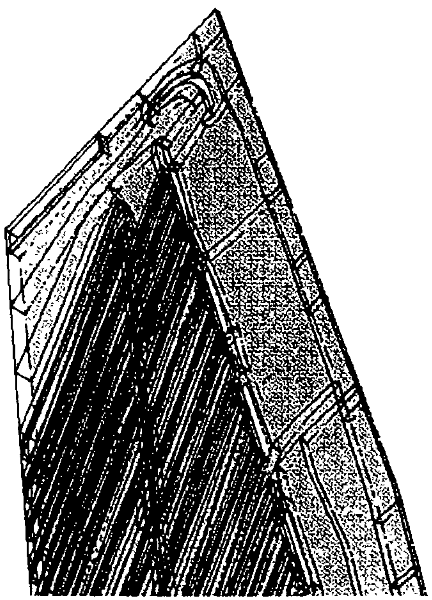
Red=high

Blue=low

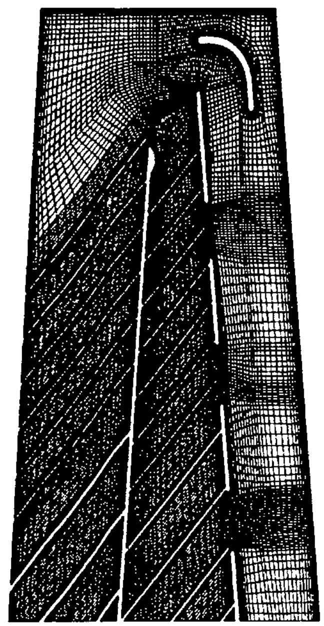
Glenn-HT Computation

Glenn-HT 3D heat transfer computations compared to experimental data near the turn in a complex turbine blade trailing edge cooling passage.

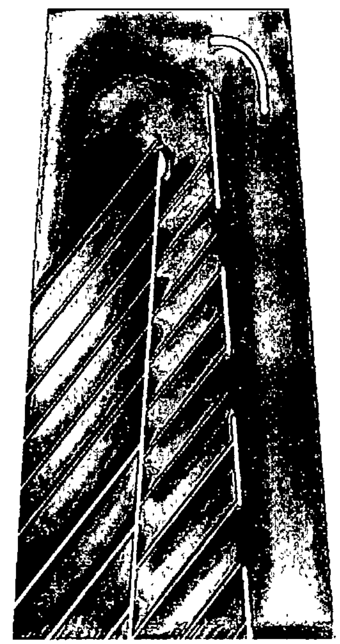
Computation used a grid of 4.5 million cells and was run using 32 processors on an SGI Origin Cluster.



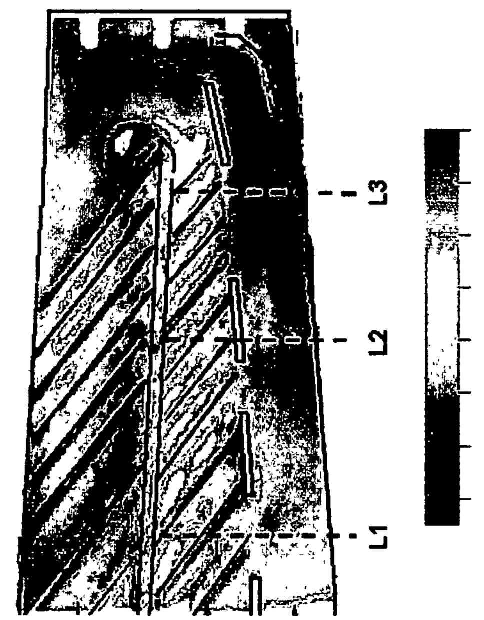
Grid Block Topology



Computational Surface Grid

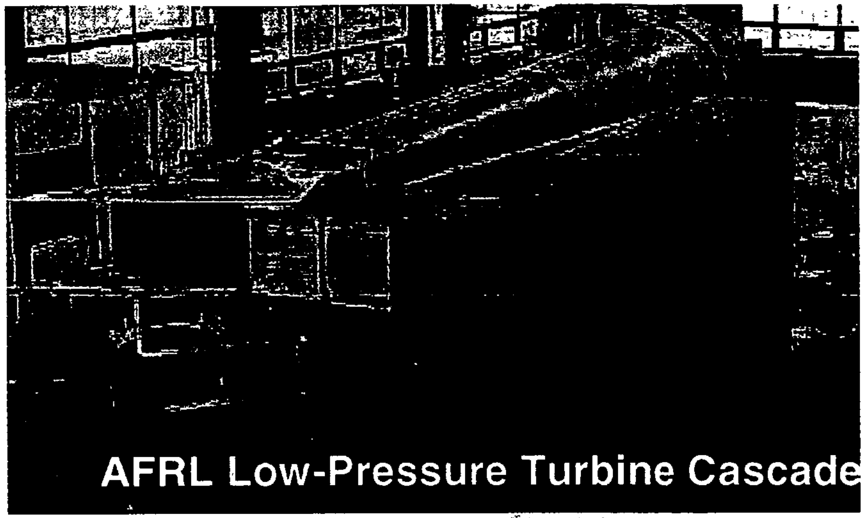


Computed Heat Transfer



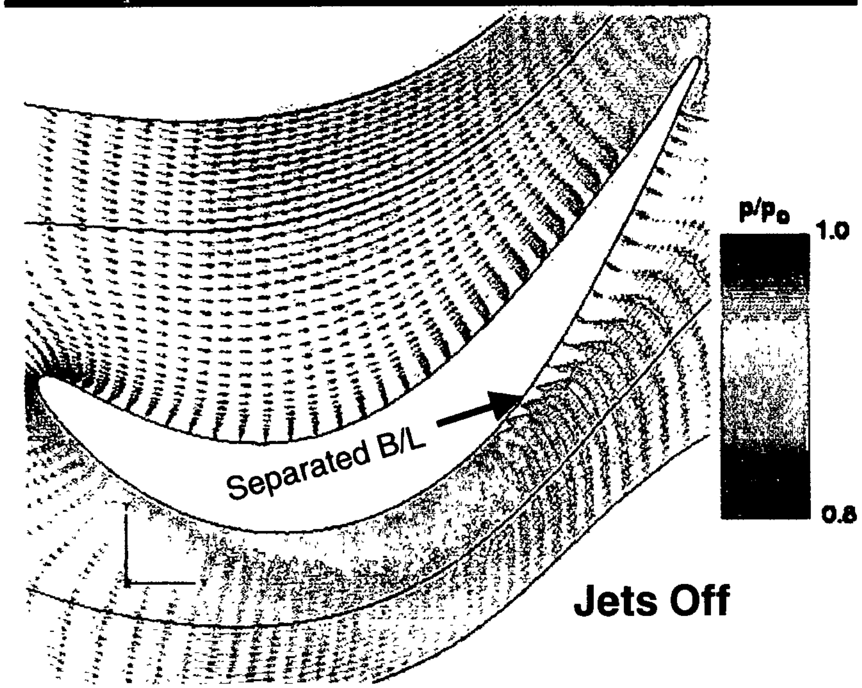
GE Measured Heat Transfer

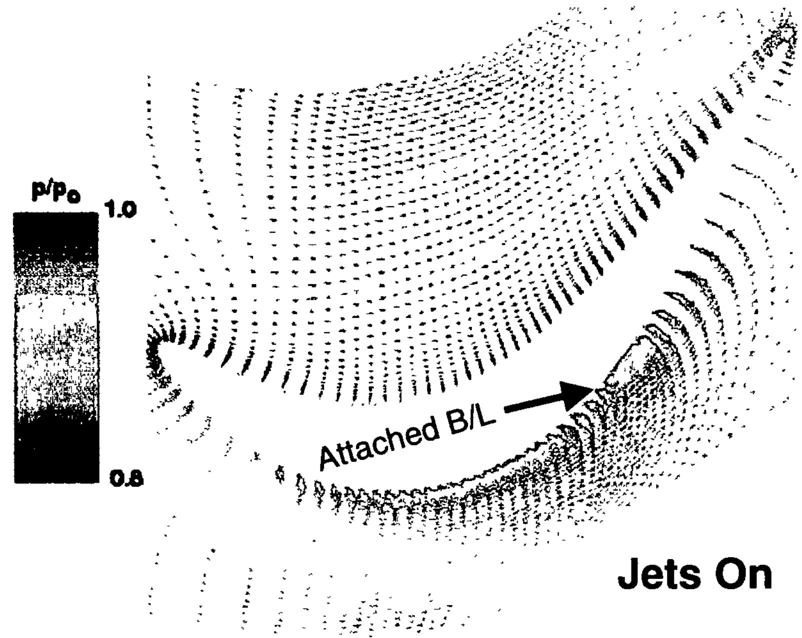
Glenn-HT Simulation of AFRL Flow Control Test



Low Pressure Turbine (LPT) Blade tested at Air Force Research Lab (AFRL)
- Low Reynolds and Mach numbers
- Boundary Layer separation on the suction side.
- Vortex generator jets (VGJ) on the blade surface induce vortices in the boundary layer upstream of the separation zone, re-energizing the boundary layer and making it resistant to separation

Glenn-HT code run with and without the VGJ
- Excellent agreement with experiment





Glenn-HT: The NASA Glenn Research Center General Multi-Block Navier-Stokes Heat Transfer Code

Future Direction

- **Unsteady vs Quasi-Steady**
- **Conjugate Heat Transfer Analysis**
- **Turbulence Model Improvements**
- **Automated Topology Generation**

Glenn-HT: The NASA Glenn Research Center General Multi-Block Navier-Stokes Heat Transfer Code

SUMMARY

- **Glenn-HT History**
- **Glenn-HT Capabilities**
- **Glenn-HT Sample Validation Cases**
- **Glenn-HT Future Direction**